Climate risk assessment in museums : degradation risks determined from temperature and relative humidity data

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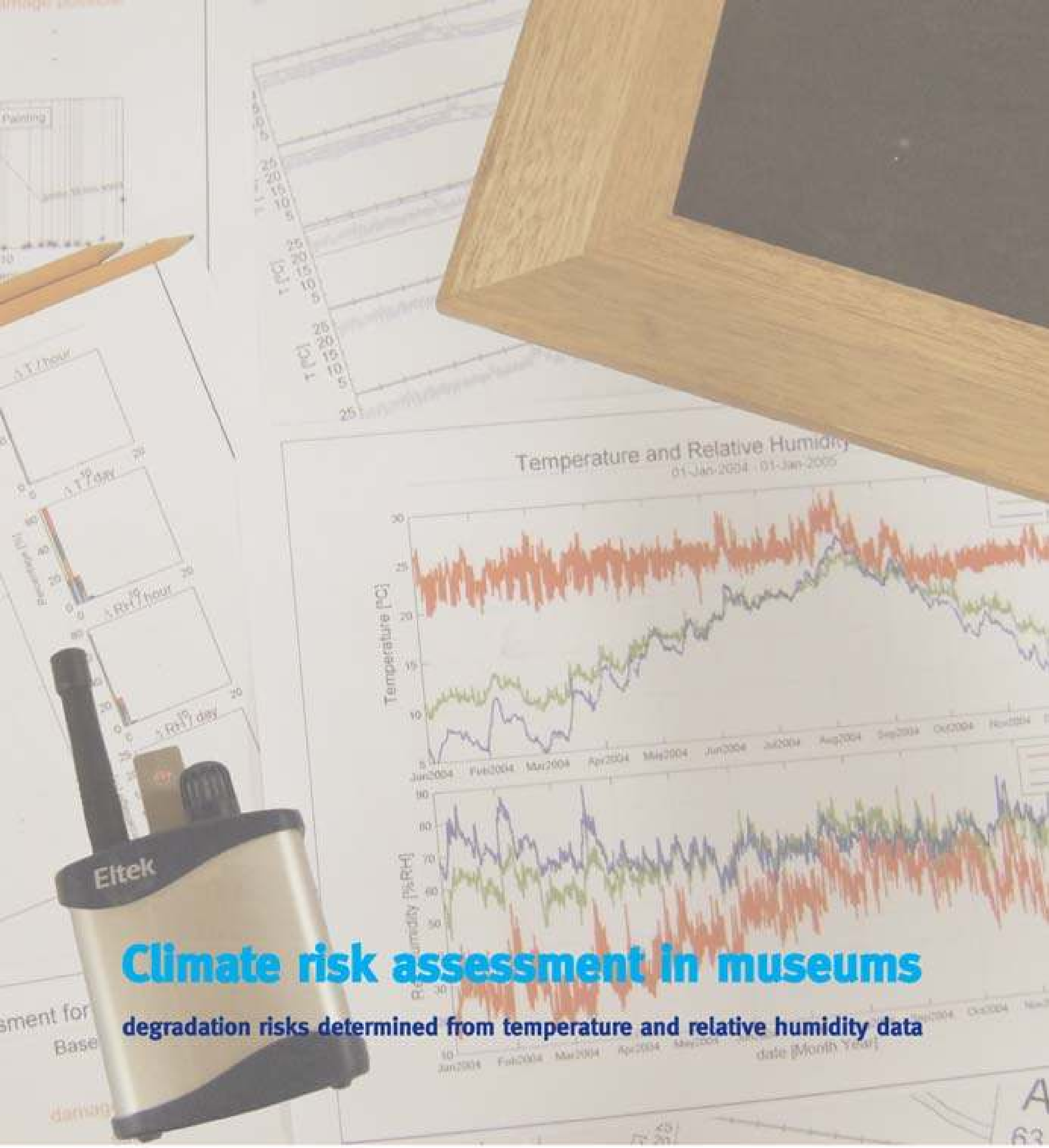

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degradation risks determined from temperature and relative humidity data

Marco Martens

/ department of the built environment

bouwstenen 161

climate risk assessment in museums

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We are not human beings
having a spiritual experience.
We are spiritual beings
having a human experience.
(Pierre Teilhard de Chardin)

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Samenvatting

Het hoofddoel van dit proefschrift is het bepalen van binnenklimaatrisico's voor museale objecten op basis van gemeten en/of gesimuleerde waarden voor temperatuur en relatieve luchtvochtigheid. De klimaatrisico's worden gekwantificeerd, zodat bepaald kan worden hoe het gesteld is met de conservering van objecten in een representatieve doorsnede van de Nederlandse musea.

In hoofdstuk 1 wordt de achtergrond van klimaatrichtlijnen voor temperatuur en relatieve luchtvochtigheid in musea toegelicht. Deze richtlijnen hebben een lange ontstaansgeschiedenis en zijn vaak erg strikt. De Nederlandse richtlijnen zijn apart onderzocht, omdat deze tot voor kort verschilden van de richtlijnen die internationaal gehanteerd worden. Bij het toepassen van klimaatrichtlijnen ontstaan diverse problemen, die kort uiteengezet worden. Deze leiden tot de onderzoeksvragen van dit proefschrift.

Hoofdstuk 2 beschrijft de methode van onderzoek. Hiervoor wordt eerst de achtergrond van het bouwproces en de ontwikkeling van klimaattechnische installaties kort toegelicht. 21 musea zijn geselecteerd op basis van hun combinatie van Kwaliteit van de Gebouwschil en Mate van Klimaatcontrole. De toegepaste meetmethode is omschreven en de gebruikte hulpmiddelen voor de analyse zijn toegelicht. Ook het Nederlandse klimaat, als randvoorwaarde voor de binnenklimaatmetingen, is omschreven.

In hoofdstuk 3 wordt de invloed van het binnenklimaat op de degradatie van museale objecten uitgelegd. De drie processen zijn biologische, chemische en mechanische degradatie. Het binnenklimaat kan beschreven worden door enkele statistische parameters, zoals gemiddelde, korte fluctuaties en seizoensfluctuaties in temperatuur en relatieve luchtvochtigheid. Daarnaast wordt een algemene klimaatrisico methode geïntroduceerd. Deze methode bepaalt welk percentage van de tijd een gemeten of gesimuleerd klimaat past binnen elke ASHRAE klimaatklasse. Alle onderzochte musea worden met behulp van deze methode onderzocht in hoofdstuk 4. Hier wordt echter geconcludeerd dat deze methode zijn beperkingen kent: de algemene klimaatrisico methode laat direct de algemene risico's van een bepaald klimaat zien, maar niet de risico's die veroorzaakt worden door een kortdurende afwijking buiten de gestelde klimaatklasse, zoals bij extreem weer of een storing in een klimaatinstallatie.

In hoofdstuk 5 wordt daarom een nieuwe methode geïntroduceerd die direct de risico's voor bepaalde objecten bepaalt uit gemeten of gesimuleerde temperaturen en relatieve vochtigheden. Biologische, chemische en mechanische degradatie worden bepaald voor vier specifieke objecten, die goed gedefinieerd en onderzocht zijn. Nu wordt ook de zogenaamde responsietijd van deze objecten gebruikt om het door de objecten ervaren klimaat te berekenen, in plaats van het klimaat rondom de objecten te onderzoeken. Een risicobenadering bepaalt of een object veilig is, mogelijk beschadigd kan raken of vrijwel zeker beschadigd zal raken door het ervaren klimaat. Deze risicobenadering bestaat uit 1) het vergelijken van het klimaat met modellen voor schimmelontkieming en –groei; 2) het bepalen van de gemiddelde relatieve bruikbaarheid als maat voor de chemische degradatie; 3) het bepalen welke vervorming elk object ondergaat en of deze vervorming binnen het elastische of het plastische gedrag van het materiaal valt en 4) het bepalen van het aantal cycli van verandering in het klimaat gedurende een eeuw om in te schatten of er schade optreedt aan de decoratieve laag. Ook deze methode is toegepast op alle gemeten klimaten; de resultaten hiervan worden besproken in hoofdstuk 6. Ook wordt deze specifieke methode vergeleken met de algemene methode. De conclusie is dat de specifieke methode eenvoudig te interpreteren resultaten geeft, die bovendien betrouwbaarder zijn dan de resultaten van de algemene methode.

Hoofdstuk 7 maakt gebruik van een computermodel om de invloed van veranderingen aan het gebouw op het binnenklimaat en de daaraan gekoppelde klimaatrisico's in te schatten. Het model gebruikt metingen van het buitenklimaat om het binnenklimaat te berekenen in alle mogelijke combinaties van Kwaliteit van de Gebouwschil en Mate van Klimaatcontrole, zoals gedefinieerd in hoofdstuk 2. De algemene en specifieke klimaatrisico methoden uit hoofdstuk 3 en 5 zijn vervolgens gebruikt om de risico's voor de museale objecten in te schatten. Allereerst is het effect van gebouwaanpassingen op de klimaatrisico's en op het energiegebruik bepaald. Denk hierbij aan het veranderen van de hoeveelheid ventilatie of het aanpassen van de dikte van wanden en de grootte van ramen. Vooral de hoeveelheid ventilatie en de totale oppervlakte van de buitengevel zijn van invloed op de collectierisico's. Ook de invloed van bezoekers mag niet worden onderschat. Vervolgens is ook de invloed van de setpoints op het energiegebruik en de risico's voor de objecten onderzocht. De klimaatinstallatie probeert een bepaalde ingestelde waarde te bereiken: het setpoint. De keuze voor dit setpoint heeft gevolgen voor de klimaatrisico's voor de objecten. Ook risico's voor het gebouw, zoals schimmel en het rotten van houten balken, hangen af van de keuze voor het setpoint. Simulaties van een goed gedefinieerde casus laten zien dat het aanpassen van de gebouwschil (verminderde infiltratie and verbeterde isolatie) het energiegebruik met een factor 8 kan laten dalen. In de praktijk zijn dergelijke wijzigingen aan de gebouwschil vaak niet mogelijk vanwege het monumentale karakter van de gebouwschil. Wanneer het setpoint afhankelijk wordt gemaakt van het buitenklimaat – met de seizoenen mee bewegend – of wanneer het verschil tussen binnenklimaat en buitenklimaat wordt gereduceerd, zijn energiebesparingen tot 23% mogelijk. De klimaatrisico's voor de objecten nemen echter niet toe, integendeel: meestal neemt de chemische degradatie zelfs af, omdat deze grotendeels afhangt van de gemiddelde binnentemperatuur. Bovendien worden de risico's bij uitval van de klimaatinstallaties hiermee verkleind.

Hoofdstuk 8 laat zien dat het mogelijk is om een binnenklimaat met weinig risico's te realiseren in alle combinaties van Kwaliteit van de Gebouwschil en Mate van Klimaatcontrole. In onverwarmde gebouwen is soms een risico op schimmelgroei; temperatuur en relatieve vochtigheid zijn vaak vrij constant en veroorzaken daarom weinig risico op degradatie. Dit wordt bovendien onderbouwd door talloze voorwerpen die al vele eeuwen in onverwarmde gebouwen bewaard zijn en die nog in goede staat verkeren. Wanneer er een verwarmingssysteem wordt toegevoegd, ontstaat een groter verschil in relatieve luchtvochtigheid tussen de seizoenen. Dit grotere verschil wordt ook ervaren door de museale objecten, want hun responsietijd is meestal korter dan een seizoen. Hiermee ontstaan middelmatige risico's op mechanische schade. Wanneer ook be- en ontvochtiging wordt aangebracht, nemen deze grote verschillen af en worden ook de risico's op mechanische schade verkleind. Zowel lokale als centraal aangebrachte klimaatsystemen kunnen voor een veilig binnenklimaat zorgen; dit is afhankelijk van de keuze voor de setpoints. Dichtbij de monumentale gebouwschil of zelfs achter een voorzetwand kunnen toch verhoogde risico's op schimmelvorming en condensatie optreden. Ook museale objecten die dichtbij zo'n buitenwand worden geplaatst, kunnen worden blootgesteld aan deze risico's. De toename van het risico nabij de gebouwschil is groter naarmate een lagere Kwaliteit van de Gebouwschil wordt gecombineerd met een hogere Mate van Klimaatcontrole.

Normaal gesproken zorgt een vitrine of een microklimaatdoos voor een stabieler klimaat rondom het erin verpakte object. Zelfs dagelijks terugkerende verschillen die worden veroorzaakt door bezonning van de ruimte of een dag en nachtregime van de klimaatinstallatie hebben weinig effect op de stabiliteit van de relatieve vochtigheid in de vitrine. De enige uitzondering is wanneer een vitrine wordt blootgesteld aan een warmtebron zoals halogeenverlichting: plotselinge en hevige veranderingen in temperatuur kunnen dan ook tot veranderingen in de RV in de vitrine leiden.

Tot voor kort waren de in Nederland toegepaste klimaatrichtlijnen erg streng; in elk geval te streng om toe te passen in monumentale gebouwen zonder tot extra problemen met de gebouwschil te leiden. De risico's voor de museale objecten zijn echter meestal klein. Dit biedt de nodige kansen: wanneer binnenklimaten wat minder strikt worden, zullen de risico's voor de objecten niet toenemen, terwijl er wel veel energie bespaard kan worden.

Een ander belangrijk probleem is de introductie van extra risico's wanneer een klimaatsysteem in een gebouw wordt geplaatst. Naast het introduceren van risico's op bijvoorbeeld lekkage van leidingen, dient ook te worden geschat wat er gebeurt bij een storing in de installatie. Het is mogelijk dat een groot deel van de collectie wordt blootgesteld aan een klimaat dat plotseling flink afwijkt van het gewenste en het gewende klimaat met alle gevolgen van dien. Dit extra risico kan ondervangen worden door een goede, onafhankelijke klimaatmonitoring waarbij automatisch alarmen worden afgegeven bij ongewenste klimaatcondities. De veiligheid van objecten blijft daarmee voor een groot deel afhankelijk van de menselijke actor: een goed management en regelmatige controles zijn noodzakelijk.

Summary

The main subject of this thesis is the determination of climate risks to objects in museums on the basis of measured and/or simulated temperature and relative humidity data. The focus is on the quantification of climate related risks for the preservation quality of indoor climate in Dutch museums.

Chapter 1 is an introduction of the background of museum indoor climate guidelines. These climate guidelines have developed over many years and are mostly very strict. The Dutch specifications, which differ from the guidelines in other countries, have been investigated. This leads to the research questions that have been examined in this thesis.

In chapter 2 the methods of research are discussed. The background of the Dutch building process and the development of systems to improve the indoor climate are provided. 21 museums were selected based on their combination of Quality of Envelope and Level of Control. The measuring method followed in each museum is provided and the analysis tools are discussed. Obviously, the main boundary condition – the Dutch weather – is also described.

In chapter 3 the effect of the indoor climate on degradation processes is described. The three most important processes are biological, chemical and mechanical degradation. Indoor climates are described by statistical parameters to provide information such as averages, short time fluctuations and seasonal fluctuations for temperature and relative humidity. The general climate risk assessment method is introduced, which analyzes climate data by determining the percentage of data that fits into each ASHRAE climate class. This method is applied to all museums investigated in chapter 4. It is concluded that the method has limitations: the general climate risk assessment method directly shows risks to objects but risks resulting from a short climate excursion e.g. extreme weather conditions or climate system failure are disregarded.

Chapter 5 introduces a new method in which measured or simulated data on temperature and humidity are directly related to risks for objects. Biological, chemical and mechanical damage are assessed for four specific, well defined objects. Now the response time of objects is used to calculate the climate the objects experience, rather than looking at the climate around the objects. Risk analysis determines whether the object is safe, possibly to be damaged or likely to be damaged when subjected to the described climate. This risk analysis consists of 1) comparing climate data to germination and fungal growth isopleths for assessing the amount of fungal growth; 2) determining the average lifetime multiplier in order to estimate chemical degradation; 3) comparing strain in objects to determine whether deformation is elastic or plastic and 4) assessing the number of cycles during a century and determine whether a first crack occurs in the pictorial

layer. This specific climate risk assessment method is applied to all museums investigated in chapter 6. Moreover, this method is compared to the previously described general method. It is concluded that this method is easy to use and that it provides more reliable results than the general climate risk assessment method.

Chapter 7 uses a computational model to investigate the influence of changes to the building on the preservational properties of the indoor climate. This model calculates the indoor climate for combinations of building type and climate system type, as defined in chapter 2, using weather data. The output is converted into risks to objects, using the methods described in chapter 3 and 5. Firstly, the effect of building adaptations on climate risks and energy use is investigated, such as thicker walls and larger windows. It is concluded that especially the influence of ventilation rate and exterior surface area have a large influence on collection risks. Furthermore, the number of visitors has an effect that cannot be disregarded. Secondly, the influence of set points is researched, both on energy use and climate risks. The climate system tries to achieve a certain target value for temperature and relative humidity: the set point. The choice for this set point value has an influence on the risks for objects. Additionally risks for the building, such as mould growth or wood rot, largely depend on this choice for set points. Simulations in a well defined case show that improving the building envelope (reducing infiltration and increasing insulation) reduces energy use by a factor 8. These changes to the building, however, might interfere with the original character of the building. By making set points for temperature and RH dependent on the outdoor climate – “following the seasons” – and in some cases lower the difference between average indoor and outdoor conditions, energy savings up to 23% are possible. The risks for objects do not increase, on the contrary: in most cases the risk on chemical degradation for objects, which is closely related to indoor temperature, decreases.

In chapter 8 it is concluded that a low risk indoor climate can be realized in almost all combinations of Quality of Envelope and Level of Control. In unheated buildings a minimal risk on fungal growth is present; temperature and relative humidity in monumental buildings are usually fairly constant and of little risk. This is also supported by the fact that lots of objects have lasted for centuries in unheated buildings. When heating is added a larger difference in relative humidity between summer and winter appears. This seasonal variation is noticed by most objects (their response time is shorter than a season); moderate risks on mechanical damage are introduced. When also humidification and dehumidification are added, the risks on mechanical damage to objects are reduced. Both local measures and centrally controlled climate systems are able to create a safe indoor climate for the objects. This is, however, dependent on the chosen set points and type of system. Close to a monumental envelope (or even behind double wall constructions) problems might arise due to fungal growth or condensation. Moreover, objects placed close to the envelope might still be exposed to high risks. This effect is largest when a lower Quality of Envelope and a higher Level of Control are combined.

A display case or microclimate case usually provides a more stable climate around the object. Risks on mechanical damage are reduced considerably. Even the daily changes caused by a day/night regime or solar radiation seem to have little effect on the objects in a display case. The only exception is when display cases are exposed to heat sources such as halogen lighting: sudden and dramatic changes in temperature might also cause fluctuations in RH.

The climate guidelines used until a few years ago were very strict; too strict to apply in most monumental buildings. Risks for most objects are however low. This is a great opportunity: guidelines can become less strict without increasing risks for objects. In addition, there is a large potential for energy savings.

Important for risk assessment is also the introduction of new risks by introducing a climate system. A system failure might expose a large part of the collection to a climate that deviates considerably from the normal conditions. This is an extra risk that calls for a proper monitoring and notification system. Safety of objects is for a great part dependent on the human factor: proper management and routine checks are necessary.

1

Introduction

In many Dutch museums a continuous process of preventive conservation takes place. Preventive conservation describes research and interventions aimed at reducing deterioration rates and minimizing risks to collections [ICOM-CC, 2011]. The activities include the renovation of buildings and the implementation of climate systems to upgrade preservation quality and visitor comfort. Temperature and relative humidity guidelines as well as loan agreements for museums are strict and therefore demand a high standard for the indoor climate. Monitoring the indoor climate, by the buildings climate control system or by an independent system, shows that despite the effort, the indoor climate is not as constant as expected. This leads to a feeling of frustration and confusion: even the best is not good enough. The overall aim of many museums is not only to *reduce* risks caused by the indoor climate but to completely *exclude* them.
The questions frequently asked by the museum staff are whether it is possible to achieve a good climate in their monumental building and what the costs of such a climate are in terms of investment and exploitation.

The title of this thesis is “Climate Risk Assessment in Museums”. This indicates a variety of topics. The indoor climate – temperature and relative humidity of the indoor air volume – in museums might be one of the main causes for degradation of museum objects. Many museums are equipped with systems that enhance the natural indoor climate. The indoor climate, however, is not uniform across the entire building. Locally climates will differ from the average climate due to solar radiation, air inlets, differences in thermal insulation and many other causes. These so-called microclimates are what the objects are exposed to. Next to museum objects also many museum buildings need to be preserved because these are important monumental structures.

This research was carried out at the Eindhoven University of Technology (TU/e), at the department of the Built Environment, unit Building Physics and Systems. The Technische Hogeschool Eindhoven (former name of TU/e) was founded in 1956. In September 1967, Bouwkunde (department of Architecture) was established [Vossers, 1972]. Physics of the built environment (FAGO) was an integral part; it focused on topics such as heat, moisture, light, materials and sound. In the early 1970’s professor Hamaker stressed that the indoor climate should be designed for the well-being of humans [Hamaker, 1971]. Human comfort became a field of interest for FAGO. Models were developed that were able to predict indoor conditions; these models were fine tuned by comparing the models output to measured values. In the mid 1980’s Schellen introduced the awareness that the indoor climate is also of major importance for the preservation of objects placed in the interior. His doctoral work “Heating monumental churches” focused not only on churches and heating systems, but also on the preservation of church organs and wooden interiors [Schellen, 2002]. Within Schellen’s field of competence “Physics of Monuments” research is performed on many different types of buildings: churches, castles, fortresses, water towers, office buildings, museums etc.

In this chapter, an introduction is given of the research carried out. In paragraph 1.1 background information is given about indoor climate in museums. This leads to a problem description in paragraph 1.2 and research questions in 1.3.

1.1. BACKGROUND

Firstly some background information is given about climate in museums. Secondly the global development of climate guidelines is explained. Thirdly the current Dutch climate guidelines are described.

1.1.1. Climate in museums

Museums and their collections are exposed to all kinds of agents of deterioration, e.g. direct physical forces, thieves, vandals, displacers, fire, water, pests, contaminants, light, UV, incorrect temperature and incorrect relative humidity [Michalski, 1994a]. It is important to determine the major risks for each object by using a systematic approach: the magnitude of risk is described as the *probability* of an effect to occur times the *fraction* of the collection that is susceptible for this effect times the *loss in value* times the *extent* of the risk [Waller, 1994]. Risk assessment is helpful to minimize confusion between what can be conserved and what needs conserving [Dollery, 1994]. A general conservation survey has proved effective in determining priorities, future strategies and leads to a long-term conservation plan which can also be used to raise proper funding [Reger & Rose, 1994]: a maintenance program avoids the need to repeat expensive restoration every 10 years [La Rocca & Nardi, 1994]. It remains however a custom made process: each collection consists of unique elements and needs an individual approach [Barclay & Antomarchi, 1994] taking into account the original use of the objects [Clavir, 1994].
It is difficult to start with risk management from scratch. Often other activities, e.g. moving (parts of) a collection, are a good occasion to reconsider collection risks and imply simple measures to improve conservation, e.g. updating inventory, labeling, creating dedicated containers [Thorp & Wilson, 1994] and removing unstable packaging [Sease & Anderson, 1994].

An important result of risk assessment is to establish whether the indoor climate causes risks to objects. Indoor climates are closely related to buildings. It is therefore important to start with the basics [Michalski, 2004]: the building. Excess moisture does not only lead to condensation: in case of bad building maintenance or flawed building design it can lead to many risks, e.g. wood rot [Westfield, 1996]. In historic buildings, moisture is the biggest issue and needs constant attention [Conrad, 1996]. Excess moisture also causes fungal growth, which depends on temperature and relative humidity [Clarke et al., 1996]. The germination depends also on the quality of the substrate [Adan, 1994 & Krus et al., 1999].
When designing or redesigning a building, the concept of zoning (division in collection space and non-collection space as well as visited and non-visited space) might be useful as a museum planning tool: parts that contain both collection and visitors demand the most attention because the climatic needs for visitors differ from the needs for the collection [Dexter Lord & Lord, 1999].

With time and changes of use, the architecture of buildings is commonly altered. The original buildings climatic performance is therefore hindered and in need of improvement. In case of museums, these improvements should aim at climatic stability and material safety; in warm, humid regions improvements should also aim at reducing heat and moisture gains indoors [Toledo, 2007].
Improving the indoor climate will require a certain amount of energy. There has been an increasing demand for energy efficiency and sustainability in buildings. This leads to research in the field of more passive ways of controlling the indoor climate. Yet there is a lack of studies on passive museum buildings, as well as a lack of consistent monitoring of climatic data [Toledo, 2007].

The indoor climate in a building is not uniform throughout the entire building. Locally climates diverge from the average indoor climate. This is caused by differences in the building envelope, orientation of the buildings or rooms, solar radiation, wind, building use etc. These local climates usually cause extra preservation problems, because it is impossible to fully control the indoor climate. Extra measures on object level might be needed. Canvas and panel paintings can be protected from climatic influences by applying a material on the back of the painting [Ligterink & Di Pietro, 1998] or by completely enclosing the painting [Wadum, 2000, Padfield et al., 2002 and ICN, 2004].
Microclimates are not always negative: sometimes it is beneficial for preservation to create microclimates. Instead of making changes to the whole building, local measures can be used to protect a single object or a group of objects. When environmentally sensitive objects need specific climate control, consideration should be given to display them in microclimate cases [Stolow, 1994]. In 1982, Michalski introduced a simple and cheap control module for RH in display cases; a small HVAC system was included in a display case [Michalski, 1982]. Also passive methods have been introduced, such as the application of silica gel [Lafontaine, 1984 and Weintraub, 2002] or microchamber paper [Hollinger, 1994] in a closed volume of air. Several wooden cases have been researched to investigate their buffering effects [Kamba, 1994]. Also museum display cases were assessed [Cassar & Martin, 1994], [Michalski, 1994b]. Pollution emitted by objects might however be damaging to objects in an airtight case [Gryzywacz & Tennent, 1994]. Since showcases prevent pollutants released by the collection materials from diffusing away, monitoring of pollutants is useful. Metal strips provide a visual indication of whether corrosive substances are present in museum showcases [Knight, 1994].
Microclimates are very effective, not only in buildings but also in circumstances in which the climate can be extreme. Microclimate cases are therefore also used for transportation of paintings [Richard, 1994].

The climate around an object – the indoor climate or a microclimate – may cause the object to deteriorate over time. Object deterioration is usually divided into biological, chemical and mechanical degradation. Much of the damage found in cultural and artistic objects results from mechanical responses to stimuli such as changes in temperature, relative humidity, impact and vibration [Mecklenburg, 1991a]. For the vast proportion of cultural objects, the materials are organic, and their mechanical properties are dramatically altered by environmental factors such as changes in temperature and relative humidity [Mecklenburg, 1991a].
Research on object deterioration should not be a major problem: material properties can be determined and composite construction of objects is nearly always evident, so objects can be modeled mathematically. Time effects depend on flow rates of heat and moisture; the effects of a changing environment may be considered

zero if the object is unharmed upon returning to the original environmental conditions [Tumosa et al., 1996].

Objects consist of one material or are composed of more materials. It is therefore important to find out how each material degrades. Some materials and processes have been researched more intensively than others. Paper, being the main content of archives, is well documented [Porck, 1999 & 2000] [Wilson, 1995]. Stresses in coatings due to temperature and RH have been researched by Perera & Vanden Eynde [1987]. Bailie [1988] investigated the fading of traditional pigments. Crack mechanisms in gilding have been researched by Michalski [1988]. Hedley [1988] described stress strain response of paint on canvas. Mecklenburg [1991b] researched mechanical and physical properties of gilding gesso. The relation between wavelength and fading of pigments has been researched by Saunders & Kirby [1994]. New and old wood and its properties are explained by Erhardt [Erhardt et al., 1996]. The response of painted wooden surfaces to changes in RH has been researched by Mecklenburg [Mecklenburg et al., 1998]. Porck [1999] researched the aging of paper [Porck, 1999]. The behavior and response of paintings with different types of lining treatment was investigated by Young and Ackroyd [1999]. Kozłowski [2007] determined climate induced damage to wood and response of wood supports in panel paintings is researched by Rachwal [Rachwal et al., 2011].

Measurements in museum spaces and near objects are needed to see whether the indoor climate can live up to the expectations of the museum. In the past, temperature and relative humidity were monitored routinely by using thermo hygrographs; data analysis was laborious and time consuming [Martin & Blades, 1994]. Electronic units are better suited in terms of flexibility and cost, but routine calibration and maintenance remains needed [Martin & Blades, 1994]. Accuracy in RH measurements is usually limited to ±5% for thermo hygrographs and ±3% for electronic hygrometers [Brown, 1994]. Setting specifications of 55 ± 5% RH are therefore unrealistic since RH levels cannot be measured sufficiently accurately; it is not taken into account whether such specifications are necessary or even achievable [Brown, 1994]. Electronic units are better suited to measure variations in RH over time than the level of RH, but it is important to take into account the response time of the unit.

Measurements are also needed for controlling the environment: reliable measurements enable the relative humidity to be controlled through heating or with the use of (de)humidifiers [Staniforth, 1987].

Monitoring can be a powerful diagnostic tool; a factual record of feedback on climate conditions. To best perform the analysis, it is necessary to first separate the building's behavior from its HVAC systems by shutting systems off for a period of time or comparing to similar buildings [Conrad, 1995d].

Measurements can also be used to determine proofed fluctuations: changes in climatic circumstances over time that did not lead to damage to the object. EN 15757 [2010] describes how to calculate these proofed fluctuations by assuming that fluctuations in between the 7th and 93rd percentile of the past climate are safe.

In practice, making the indoor climate suitable for the preservation of objects is difficult. Care of artifacts sensitive to RH in historic buildings requires a different approach than in buildings designed as museums [Staniforth et al., 1994]. In historic buildings it is very difficult and expensive to install air-conditioning, and maintenance and running costs are high in terms of energy and personnel [Oreszczyn et al., 1994]. In National Trust monumental buildings heating systems are operated on RH-priority (except in storage areas: dehumidification is used there) [Staniforth et al., 1994]. This method of heating increased protection of the collection, lowered potential damage to the building and costs less energy and maintenance in comparison to conventional methods of control [Smith, 1999].

Another possibility is to establish high temperature and moisture inertia: a storage area is developed in which fresh air is only drawn in when its water content will steer the interior towards the specified RH [Padfield & Klens Larsen, 2005]. Passive climate control, using building materials to moderate variation in both temperature and relative humidity has been shown to work in archives, which have a small air exchange rate and can be allowed to get colder than humans find congenial [Padfield, 2007].

Measures which promote the preservation of either the historic structure or the artifacts at the expense of the other, should not be considered – Principle Five of the New Orleans Charter [Michalski, 1998].

It is simply not possible to give the occupants, the artifacts and the building their temperature and humidity *wants*, except in rare circumstances. It is possible, however, to give all three groups most of their *needs* throughout most weather conditions [Michalski, 1998].

1.1.2. Standards and guidelines

In the paper "Humidity and moisture in historic buildings", Brown and Rose [1996] describe the development and evaluation of indoor climate standards and the need for control in museums. Traditional museum humidity specifications have developed empirically as control of the indoor environment became more sophisticated during the twentieth century. During dry periods, caused by winter heating, the flaking of paintings increased. During World War II the collection of the National Gallery in London was moved to the Manod grove. The conditions in the quarry turned out to be beneficial for the collection; the repairs needed to keep the paintings in their original condition reduced considerably. After the war, when the paintings were returned to the Gallery, the degradation process returned to normal and the flaking and blistering started again.

The reduction of mechanical damage by controlling the climate around objects coincided with the technical advancements of the 1950's. Technical equipment to influence both temperature and humidity of the indoor climate made it possible to obtain just about any indoor climate, regardless of the outdoor climate.

After WWII limited research was performed on panel paintings that were subjected to faster and slower changes in relative humidity. A value of 55%RH to 60%RH was considered to be the optimum set point. In "The museum environment" by Thomson [1986] an average value of 55%RH and an acceptable fluctuation of plus or minus 5%RH are presented. Thomson also made a very important remark:

"There is impressive general evidence, for example in the records of the National Gallery, London, that transferring paintings to an air conditioned environment very greatly reduced the need for treatment of detached paint ... But the question of how constant RH needs to be to ensure that no physical deterioration will occur remains at present unanswered. The standard specification of ± 4%RH or ± 5%RH control is based more on what we can reasonably expect the [air conditioning] equipment to do than on any deep knowledge of the effect of small variations on the exhibit. … Choice of RH level depends on several factors but cannot go too far from 50%RH or 55%RH. An exception may be found in the very low winter temperatures of Canada and north-eastern Europe where attempts at humidification to this level may endanger the building."

The value of 55%RH was deliberately chosen because it is the yearly average value of most European spaces that are heated [Brown & Rose, 1996]. Also it was known that extremes in humidity (either very low or high) cause high risks on mechanical damage due to change in material dimensions. A fluctuation that doesn't cause damage at objects subjected to an average humidity of about 55%RH might do so at an average of 70%RH. Therefore it is considered safer to keep objects in the middle RH region [Mecklenburg & Tumosa, 1991].

Many institutions created their own set of 'optimum' guidelines [Alaska State Museum, 2000], [Michalski, 2000], [Jütte, 1994]; most of these guidelines were based on Thomson.

The last decade shows an increased awareness that very strict climates are very hard or even impossible to reach in museum buildings [Brown & Rose, 1996]. Also energy conservation is getting more important. Controlling the environment is a large component of current museums energy consumption and carbon emissions. A lot of savings can be made if we 1) adjust performance criteria specific to the location; 2) implement broader criteria; 3) account for passive features rather than mechanical systems; 4) improve or enhance the building envelope; 5) evaluate new or alternative management strategies [Henry, 2007]. Thomson already predicted this to happen [Thomson, 1986]:

"There is something inelegant in the mass of energy-consuming machinery needed at present to maintain constant RH and illuminance, something inappropriate in an expense which is beyond most of the world's museums. Thus the trend must be towards simplicity, reliability and cheapness."

Minimalistic conservation should be considered, in which even 'do nothing' can be an option as long as it is done consciously [Staniforth, 2007].

There is a growing awareness that strict climate guidelines are not needed per se. For instance, environmental parameters specified by lenders to exhibitions can be very restrictive but may not relate closely to the recent environmental history of the object or to the sensitivity of the object to changes in temperature and relative humidity [Ashley-Smith et al., 1994].

Another fact against strict guidelines is that the extension of the small fluctuation criterion to all artifacts has no merit except convenience. For collections dominated by rigid organic materials we must accept that the data supports common sense, not magic numbers. If tight control sacrifices long-term reliability of the 25%-75% RH limits, or other issues like fire and pests, it is counter-productive to the total well-being of most collections [Michalski, 1993]. The allowable fluctuations derived from research are larger than those generally presently recommended, even though these values are still extremely conservative. These values assume full restraint of the materials, long term exposure to the RH extremes, and produce changes that are well within the reversible elastic range [Erhardt et al., 1995].

Poor definition of standards and a lack of understanding of the underlying physics lead to irrational, expensive and sometimes damaging distortion of the way museums are built and operated. The RH standard is so strict that it can only be attained with mechanical air-conditioning. A 50% RH standard is high enough to cause condensation damage to buildings in cool climates yet low enough to cause damage to objects that have attained a stress free condition at a high RH in a church or a historic house [Padfield, 1994].

1.1.3. The Dutch situation

Until recently the Dutch situation was based on the ideas provided by Thomson [Thomson, 1986]. The Dutch laws on conservation did not (and still do not) contain any specific climate specifications but act as a framework for the preservation of cultural objects – the Heritage Preservation Act of 1984 (NL: Wet tot behoud van cultuurbezit) – as well as for monumental buildings – the Historic Buildings Act of 1988 (NL: Monumentenwet). In contrast, the Law on Dutch archives (NL: Archiefwet) *does* provide strict climate guidelines. The absence of an absolute guideline for museums combined with the goal of achieving optimal conservation lead to narrowing of the allowed climatic fluctuations thus ending up with stricter climate specifications.

In 1988 the Netherlands Court of Audit (NL: Rekenkamer) noted that the preservation of Dutch collections was not properly carried out. Registration, preservation, restoration, accommodation and security were mentioned as key factors for improvement. The Deltaplan [‘d Ancona, 1990] was introduced to pinpoint these factors. Starting in 1990, the Dutch government funded modifications and upgrades to the rijksmuseums (museums owned by the government) and partly (up to 40%) for non-rijksmuseums. Again, indoor climate specifications were not defined in the Deltaplan standards. This led to an individualistic approach in which each museum chose the guideline that was best suited for their needs. These guidelines tend to be on the safe side for objects, so very strict climate specifications resulted.

In 1993 all rijksmuseums became independent, but remained under supervision of the Dutch government. Nowadays the Cultural Heritage Inspectorate (NL: Erfgoedinspectie) still evaluates the care and management of the State collections. It monitors registration, preservation, storage and risk management.

To achieve the goal of optimal conservation, museums liked the idea of having a target to reach in terms of indoor climate specifications. To provide in this need the Central Laboratory for Research on Objects of Culture and Science (CL) – currently part of RCE (NL: Rijksdienst Cultureel Erfgoed) – published ‘Passive conservation; climate and light’ [Jütte, 1994]. These guidelines were based on Thomson and only the optimal climate for the most sensitive object for each material group was given. This guideline is so strict that it is impossible to implement in monumental buildings. Many museums tried to imply these guidelines, often also for objects that are not so sensitive. This led to damage to the monumental building, loss of space in the building, ever increasing energy costs and problems near the building envelope which didn’t exist before.

Rijksmuseums are often located in monumental buildings. These buildings are in most cases owned and maintained by the government building agency (NL: Rijksgebouwendienst). When a museum asks for an improved indoor climate, the Rijksgebouwendienst must provide for the necessary changes to building and climate system. The Rijksgebouwendienst also came up with guidelines for the indoor climate [Rgd, 1995]. These were however not based on collection needs, so they cannot be compared to the CL guidelines.

More and more the Cultural Heritage Inspectorate (CHI) became aware that the real indoor climate measured during the inspections diverged from the climate specifications as wished by the museums. Furthermore the CHI was only able to measure the climate during the day, while at night different climates might exist. In 2003 the TU/e was contacted by the CHI. From 2003 to 2006 a research project was conducted in three museums focusing on a) the actual indoor climate and b) the human actor in the indoor climate. This confined study was carried out by CHI to study the procedure part [Meul, 2007] in collaboration with the TU/e for the building physics [Martens et al., 2007]. Results showed that the presence of a climate system with narrow specifications leads to a false feeling of safety in the museum: the system takes care of the climate so the conservation will be okay. But due to malfunctioning of systems, irregular maintenance or the existence of local microclimates objects might still be at risk. Moreover, these systems can lead to more dramatic deviations from the average climate than before, because the indoor climate differs from the natural climate and systems have a large capacity to enhance the conditions. There is a need for a common approach, based on risk management, to provide tailor made climate specifications.

One of the recommendations of this report was the establishment of a multidisciplinary group to formulate the new museum climate approach based on the international trends. In 2007, the Netherlands Institute for Cultural Heritage (ICN) collaborated with other Dutch institutions – Cultural Heritage Inspectorate, Netherlands Museum Advisors Foundation, National Service for Archaeology, Cultural Landscape and Built Heritage (nowadays RCE), Rijksgebouwendienst and Eindhoven University of Technology – and formed the Dutch Climate Network (NL: Klimaatnetwerk). The need for an integrated climate approach is combined into a risk analysis procedure for the Dutch situation in the publication Klimaatwerk [Ankersmit, 2009], that currently is the Dutch guideline.

Another recommendation was to relate the measured climate directly to the conservation of objects. Also the three buildings examined did not provide enough data to generally assess the Dutch museum climate; more samples were needed, resulting in the research presented in this thesis.

1.2. PROBLEM DESCRIPTION

The climate specifications currently used in most Dutch museums are tight. This is caused by the fact that small fluctuations in temperature and relative humidity have proven to reduce risks on mechanical damage to objects. Also the need for visitor comfort plays an important role in museums. Another cause is the loan agreement: to be able to borrow an object, the indoor climate needs to fulfill the specifications provided by the lending museum.

The problems that occur due to these tight specifications are that the building is not really suited to cope with a strict climate (air leakage, thermal bridges), that climate systems consume a lot of useful space and are difficult to integrate in the building and that energy costs to keep the systems running are high. Moreover, extra risks are introduced in case of malfunctioning of a climate system, especially when no independent monitoring of the indoor climate is performed so malfunctions are not noticed immediately.

The need for extra information on real indoor climates in museums is therefore high. Knowhow about the influence of building quality and type of climate system on the indoor climate would be helpful in order to understand the most important aspects that influence the indoor climate.

1.3. RESEARCH QUESTIONS

The problems described previously lead to six research questions. This paragraph sums up these questions and explains them.

1. When evaluating the preservation qualities of an indoor climate, are climate guidelines a good substitute for an object oriented approach?

Climate guidelines specify a climate by imposing an average temperature and relative humidity and a maximum fluctuation in both. The risks for degradation due to this climate are given; therefore the impact of a climate on the preserved objects is known. The problem is that a measured climate often does not meet the guideline for 100%. This makes risk assessment difficult, because of the possible impact of the period out of the guideline specifications. Moreover, guidelines apply to the average indoor climate. Objects might however experience an unknown microclimate. Chapter 3 and 5 study the preservation qualities of the climate.

2. Is it possible to predict preservation qualities using measured or simulated indoor climate and how can this be done?

Many laboratory studies have been carried out that linked climate to damage. Most studies however used a fictive climate. Mechanical degradation, chemical degradation and mould growth can be assessed individually. For some typical objects, degradation data is available for all three degradation processes. Linking these studies should provide a proper degradation prediction for the object. Chapter 3 and 5 focus on this subject.

3. What influence does the building type have on preservation of objects in the Dutch situation?

Conrad and Kerschner [ASHRAE, 2007] divide the North American buildings in 6 building types, which all have a different need for climate control towards a maximum climate class that can be achieved. The museum buildings in The Netherlands – and also in the rest of northern Europe – differ from the building types found in North America. Chapter 2 will go more deeply into this topic. It is expected that the preservational properties of the indoor climate will result in the Dutch buildings under examination to be divided into a few separate classes.

4. Are simulated indoor climates as accurate as measured indoor climates in predicting preservation?

Many computer simulation tools are available that are able to simulate the indoor climate. In most cases, the simulated climate does not meet the measured climate exactly. It is important to find out whether the degradation predicted using the measured indoor climate shows similar results as the degradation predicted out of the simulation. Chapter 7 goes into this topic.

5. What physical parameters of the building have the most influence on the prediction of preservation?

Physical factors of the museum building, such as infiltration rate and insulation value, determine the indoor climate and/or the energy use of the climate system. It is important to find out what factors have the most influence. Therefore a sensitivity analysis of input parameters of the simulation model is used. Chapter 7 focuses on parameter sensitivity and on differences in buildings and systems.

6. What is the influence of set points for temperature and relative humidity on the degradation of objects and the energy use?

When improving the indoor climate using systems, set points are the target values that the climate systems are trying to reach. It is expected that the choice for these set points has a large influence on energy consumption. For the collection set points are not very important, because degradation risks for the collection are usually encountered when the system malfunctions. Degradation of the building, however, has a direct connection with these set points. The influence of making minor changes to these set points on energy use and degradation risks is examined in chapter 7.

1.4. OUTLINE

Chapter 2 of this thesis deals with the method of research. In chapter 3 a literature survey on object deterioration is performed; two ways of determining risks to a collection of objects are introduced: statistical operations and a general climate risk assessment method. Results for both are discussed in chapter 4; measurements in many museums are compared and problems are addressed. Chapter 5 proposes a new method that is based on how specific objects react to the indoor climate: the specific climate risk assessment method. Results for this method are discussed in chapter 6; moreover these results are compared to the results of the previous methods. Chapter 7 focuses on simulation of indoor climates; simulation is used to predict preservation quality of indoor climates. Furthermore simulation is also used to determine the influence of building envelopes, climate systems and set points on energy use and preservation quality. Finally conclusions and recommendations are provided in chapter 8.

2

Method of research

The goal of this research is to be able to assess the preservation quality of the indoor climate in different types of buildings with different types of mechanical climate control systems. To be able to predict preventive preservation properties in Dutch museums, it is important to carefully select museums based on their building type and climate system type. In paragraph 2.1 various building and climate system typologies are discussed; a typology based on the Dutch and Belgian situation is presented. This typology is used to select museums for this research and also to be able to distinguish in preservational aspects. For each museum investigated a common approach – described in 2.3 – is used in such a way that the outcome of all museums can be compared. The last part of this chapter focuses on tools developed for displaying indoor climates.

2.1. BUILDING AND SYSTEM TYPES

In order to come to a meaningful typology of buildings and systems, first the background of both is discussed. Then some commonly used typologies are discussed and a new typology is deduced.

2.1.1. Background on building

The Netherlands has a rich architectural history. A lot of monumental buildings are still in use all over the country; some of these buildings have a museum function. Of all 773 Dutch museums [CBS, 2007], 90% is located in a monumental building.

Building envelopes form the barrier between the indoor and outdoor climate. This envelope has a buffering and insulating effect on both temperature and relative humidity. Moreover, building envelopes make the building airtight to some extent. These effects are largely dependent on the characteristics of building materials used in the envelope.

From early on, the main building materials used were brick, stone, wood, iron, lead and glass. Lime based mortar was used to cement bricks and stones together and the indoor finishing also was lime based or made of wood. The roofs were tiled using slates or ceramic tiles. A lot of effort was put in designing buildings that would last for centuries, with specific measures to cope with the climate [Koller, 1994].

During the 18th and 19th century window frames and detailing of buildings became more sophisticated and buildings became more elegant, but most of the materials used were the same as before. Only the method of construction – the detailing – advanced during the years.

Technological advancements provided new materials that slowly found their way into the building process. In the early 20th century lime was replaced by cement. Also the buildings were built lighter with less massive walls. To prevent penetration of rain through these thinner walls a cavity was applied. Also other new materials were introduced. Around 1870 concrete was added as a building material, a little later steel and aluminum. The main construction material, however, remained brick.

The energy crisis in the 1970's made people more aware of energy losses in buildings. This was the reason for the development and use of different building materials that reduce the influence of the outdoor climate and prevent thermal bridging and condensation problems, e.g. insulation. Most of these thermal insulation materials are placed in the cavity of the walls and roofs. Also double glazing became more frequently used to prevent heat loss and condensation, but also to increase comfort. Prefabricated window frames made of aluminum got a thermal separation to prevent condensation and heat loss from the inside to the outdoors. Vapor barriers were introduced to prevent internal condensation in the insulated construction.

Nowadays the focus is on sustainability of the building stock. Newly built buildings use all kinds of techniques to reduce the amount of energy used even further. The construction is made airtight, double or triple glazing is used in the window panes and a balanced ventilation system is compulsory to supply the amount of fresh air needed for people to breath. The government plays an important role in this process; governmental buildings, including museums, are supposed to set the standard in sustainability.

2.1.2. Background on climate systems

Controlling the indoor climate in buildings is an old topic. Wealthy ancient Romans circulated water from aqueducts through walls to cool their houses. The 2nd century Chinese inventor Ding Huan invented a rotary fan for air conditioning and in 747, Emperor Xuanzong had the Cool Hall built in the imperial palace, which is described as having water-powered fan wheels for air conditioning as well as jet streams of water from fountains. [Needham, 1991]

Cities in ancient Greece used central heating systems, conducting air heated by furnaces through empty spaces under the floors and out of ducts in the walls. This hypocaust system was used in the Mediterranean region for many centuries. By the 12th century, engineers in Syria introduced an improved central heating system, where under-floor ducts were used instead of a hypocaust. This central heating system was widely used in bath-houses throughout the medieval Islamic world. [Hugh, 1985] The well-preserved Royal Monastery of Our Lady of the Wheel (founded in 1202) on the Ebro River in Spain provides an example of a central heating system using river diversions combined with wood-fired furnaces.

By about 1700, Russian engineers had started designing systems for central heating based on hydrology. The Summer Palace (1710–1714) of Peter the Great provides the best still existing example.

In 1758, Benjamin Franklin and John Hadley conducted an experiment to explore the principle of evaporation to rapidly cool an object. They confirmed that evaporation of highly volatile liquids – such as alcohol and ether – could be used to lower the temperature of an object past the freezing point of water. They conducted their experiment with the bulb of a mercury thermometer as their object and with a bellow used to quicken the evaporation; they lowered the temperature of the thermometer bulb down to -14ºC (7°F) while the ambient temperature was 18ºC (65°F). Franklin noted that soon after they passed the freezing point of water a thin film of ice formed on the surface of the thermometer's bulb and that the ice mass was about a quarter inch thick when reaching -14ºC. [Franklin, 1758]

In 1820, British scientist and inventor Michael Faraday discovered that compressing and liquefying ammonia could chill air when the liquefied ammonia was allowed to evaporate. In 1842, physician John

Gorrie used compressor technology to create ice, which he used to cool air for the patients in his hospital in Apalachicola, Florida. He hoped to use his ice-making machine to regulate the temperature of buildings. He was granted a patent in 1851 for his ice-making machine. [Jones, 1997]

Around this time most Dutch buildings were not centrally heated at all. In masonry houses, the heavy construction prevented low winter and high summer indoor temperatures. Locally the thermal comfort was increased by using a fire place to burn wood, peat or coal; this fire place was also used for cooking.

During the 19th century the first central heating systems were introduced. The first systems used steam to heat metal radiant bodies that were placed in each room. Shortly after, water was used instead of steam.

In 1902, the first modern electrical air conditioning unit was invented by Willis Haviland Carrier. He began experimentation with air conditioning as a way to solve an application problem for a publishing company in Brooklyn, and the first "air conditioner" began working 17 July 1902. Designed to improve manufacturing process control in a printing plant, Carrier's invention controlled not only temperature but also humidity. Carrier used his knowledge of the heating of objects with steam and reversed the process. Instead of sending air through hot coils, he sent it through cold coils (ones filled with cold water). The air blowing over the cold coils cooled the air, and one could thereby control the amount of moisture the colder air could hold: the humidity in the room could be controlled. The low heat and humidity were to help maintain consistent paper dimensions and ink alignment. Later, Carrier's technology was applied to increase productivity in the workplace, and The Carrier Air Conditioning Company of America was formed to meet rising demand. Over time, air conditioning came to be used to improve comfort in homes and automobiles as well.

The first systems used in museums to modify the air conditions were used to filter the air. The outdoor air was contaminated by sooth and sulfur from the burning of wood and coal. Water sprays were used to clean the air from these pollutants. By controlling water temperature, the relative humidity of the indoor climate could be controlled. In 1908 this method was used for the first time in a museum in Boston. [Brimblecombe, 1987]

In the Netherlands the Rijksmuseum in Amsterdam, designed and built in between 1863 and 1885, had a heating system installed. Natural ventilation was supposed to lead air through a stone ‘humidifying’ room to add moisture to the heated air. This system depended largely on wind speed and direction and was not very effective; over the years various changes were made to the system. This was of little avail: dry conditions in winter led to damage to furniture. Only after 1969, a new air handling system provided a satisfactory indoor climate. [Huijts et al., 1985]

2.1.3. Combination of buildings and systems

Modern technology provides a lot of freedom to the architect. Because of sophisticated materials and advanced climate systems, many climate system designs lead to a comfortable indoor climate that also provides for a reasonable amount of preventive preservation of objects. Nowadays ancient building techniques, such as the careful placement of windows to prevent direct solar radiation on art and the use of thermal and hygrical mass to buffer the climate, are often disregarded.

It is important to note that not all combinations of building and system are logical or possible. In chapter 21 of the ASHRAE handbook [ASHRAE, 2007], a table [Conrad, 1995a] is incorporated that states various types of buildings and the type of control that is possible in each building type. For each building type a suggestion for a climate system is given and the effect on preservational properties of the indoor climate is estimated (Chapter 3 will go into that). A copy of this table is presented in table 2.1. This table is very important, because these combinations are examples based on experience. For each building type a reasonable system is suggested, taking into account the limitations provided by the building and the outdoor climate. Installing a more advanced system in a building will probably not lead to an improved climate because of these limitations.

Table 2.1: Classification of climate control potential in buildings [ASHRAE, 2007 & Conrad, 1995a].

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

For the Dutch situation, however, this table is too limited. Most Dutch museums buildings are of type IV. According to Conrad, this type of building is suitable for low level heating, some summer cooling and a limited amount of humidification. The building is not used in winter. In contrast, Dutch museums have various types of climate systems, from simple heating to full HVAC systems. Also the Dutch climate is benign when compared to Conrad's North American climate and few museums close during the winter season.

Another way of categorizing buildings is based on their period of construction. Table 2.2 shows 4 periods, marked by the beginning of the 20th century, the Second World War and the 1970's energy crisis. As was mentioned in paragraph 2.1.1, the first period is traditional in its building method. After 1900, a cavity is introduced and steel and concrete come available. After WWII more new materials are used. Only after 1975, insulating materials are generally applied and traditional materials are improved.

Table 2.2: Building types based on construction period.

Type	Year	Glazing		Brickwork		Wood	Iron	Concrete			Steel		Aluminum		Insulation	Other
		Single	Double	Without cavity	Cavity			Solid	Reinforced	Prefabricated	Not insulated	Insulated	Not insulated	Insulated		
1	< 1900	X		X		X	X									
2	1900 – 1945	X		X	X	X		X			X					
3	1945 – 1975	X	X		X	X		X	X		X		X			
4	> 1975		X		X	X		X	X	X		X		X	X	X

Unfortunately, this table does not take into account the fact that old building envelopes may have been optimized during their lifetime. Buildings are reconstructed, renovated and also the envelope might benefit from that, improving thermal and hygrical behavior.

Table 2.3: Climate system complexity [Ankersmit, 2009].

Type	Ventilation		Thermal		Hygrical		Transport medium			Control		
	Natural	Mechanical	Heating	Cooling	Humidification	Dehumidification	None	Water	Air	Thermostat	Hygrostat	Building Management System
1	X						X					
2	X		X					X		X		
3	X		X		X	X		X		X	X	
4	X		X					X			X	
5	X		X		X	X		X			X	
6		X	X					X	X	X		
7		X	X	X				X	X	X		
8		X	X	X				X	X	X		X*
9		X	X		X	X		X	X	X	X	X
10		X	X	X	X	X		X	X	X	X	X
11		X	X		X	X		X	X	X	X	X*
12		X	X	X	X	X			X	X	X	X*

* = control per zone

When looking into climate systems, the ones used in museums are categorized by using Ankersmit's table [Ankersmit, 2009] as displayed in table 2.3.

For New York State museums, Lull and Banks [1990] made another distinction between systems:

- Level 1: Heating with 24-hours winter humidification, ventilation and particulate filtration;
- Level 2: Winter heating 24-hours, 24-hours summer cooling with reheat for dehumidification, 24-hour winter humidification, 24-hour air flow and improved particulate filtering;
- Level 3: Heating, cooling, dehumidification, humidification and superior particulate filtering, available 24-hours a day in any season, in a humidity-tolerant building envelope;
- Level 4: Level 3 system plus the addition of gaseous pollution control, cooling / heating / dehumidification / humidification capacity to hold close-tolerance environmental conditions at all times, and better industrial grade controls.

They specifically add that heating only, without humidification in winter, only makes the climate worse due to very low winter RH values indoors. The New York climate is colder than the Dutch climate; in the Netherlands heating without humidification is less problematic. Another disadvantage of this distinction in systems is the fact that all levels are based on air handling systems (ventilation including particulate filtration), while in Dutch museums often mobile systems are used in combination with natural ventilation.

2.1.4. Choice and description of types

For this thesis another typology of building and system types is introduced. As described above, only looking at the year of construction has some disadvantages. Here the focus is on envelope age (table 2.2) as well as changes made to the envelope. Moreover, only the envelope is looked at, not the other construction materials of the building.
Old envelopes are envelope types 1, 2 and 3 in table 2.2. Only envelopes built after 1970 are considered modern. Thus 'Quality of Envelope' (QoE) is here described as:

- *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 this thesis, the typology for climate systems is based on their effect on the indoor climate. There is a large range of climate systems for museums. It is difficult to distinguish between these systems for most conservators. The typology needs to be simple, robust, and understandable and must lead to a few clearly defined classes. Thus 'Level of Control' (LoC) is here described as:

- *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. It matches type 1 from table 2.3.
- *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. It includes types 2, 4, 6, 7 and 8 from table 2.3.
- *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). Table 2.3 types 3, 5, 9 and 11 are part of LoC 3.
- *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. Types 10 and 12 of table 2.3 are in this LoC.

Rooms with only (de-)humidification equipment without heating and/or cooling are rare in Dutch museums. In case of RH control alone, conservational heating is used in some museums. In this case the heating set point is calculated using the humidity ratio of the air and the desired relative humidity. This is a heating system in which RH is leading; a qualification in LoC 3 would be appropriate. Mind that visitor comfort is lower than in other systems, because indoor air temperatures drop during dry outdoor air conditions (e.g. during cold periods).

2.1.5. Museum classification matrix

The museum classification matrix, displayed in figure 2.1, consists of two dimensions: on the horizontal axis the Level of Control, the vertical axis Quality of Envelope. Each building – or rooms individually - can be placed inside this matrix; differences between research locations can be seen instantly.

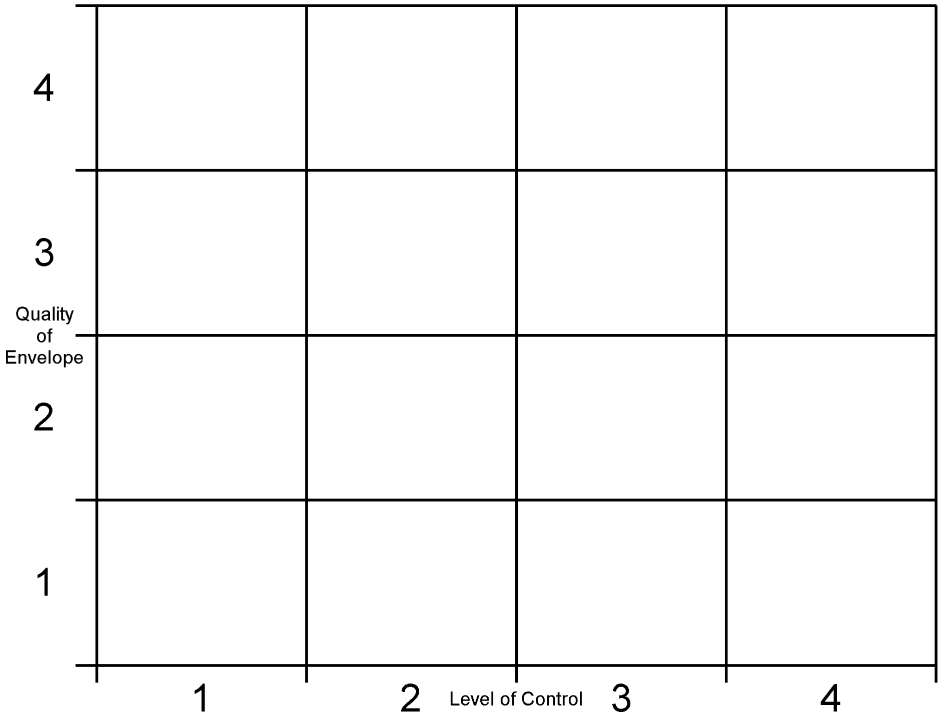


Figure 2.1: Museum classification matrix, combinations of QoE and LoC.

2.2. DESCRIPTION OF MUSEUM CHOICE

In total 21 museums have been investigated. These 21 museums were chosen for their position in the museums matrix as presented in the previous paragraph. Some museums fit into more than 1 combination of QoE and LoC; each room is placed in the matrix separately. The museum buildings are located in the Netherlands or in Belgium, within 50°47’ to 53°12’ latitude and 4°11’ to 5°50’ longitude.

First a short description of the museums is given:

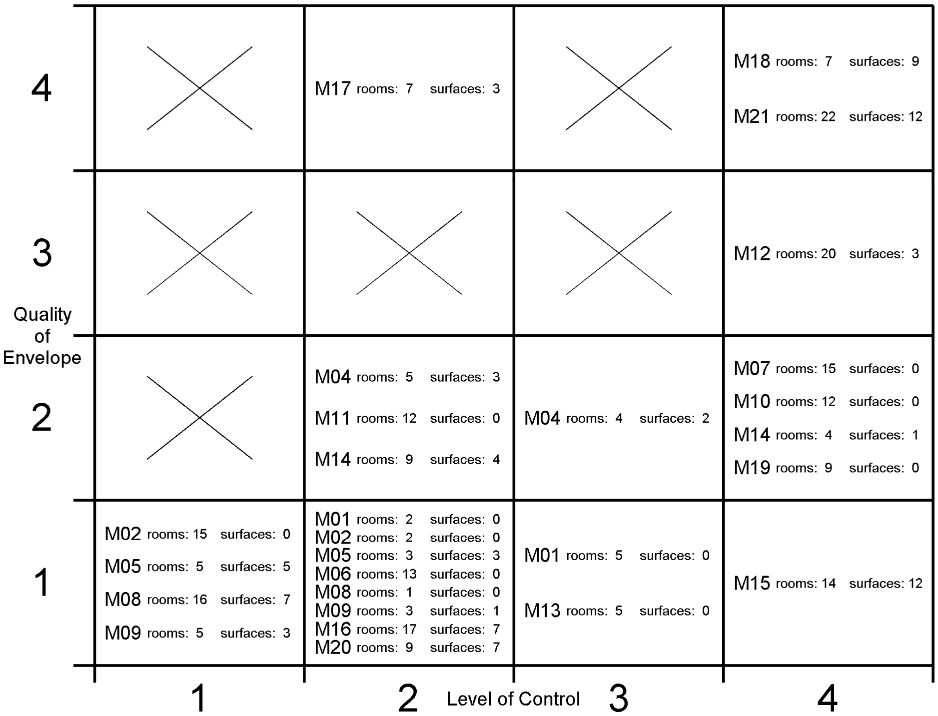
Museums with QoE 1 (museums 1, 2, 5, 6, 8, 9, 13, 15, 16, 20) all have an original, unchanged (only restored) envelope. Climate systems range from no system at all to full HVAC systems. Floor heating, air heating, radiator panel heating, gas stove heating and core heating are used in some of these monuments. In about half of these monuments RH is actively controlled.

Museums with QoE 2 (museums 4, 7, 10, 11, 14, 19) have improved air tightness and double glazing in a large part of their building. All buildings are heated; some even have full air conditioning. Systems range from panel radiators to displacement ventilation.

Museum 12 is the only museum with QoE 3. It has a double façade and a full HVAC system.

Museums with QoE 4 (museums 17, 18, 21) are recently built museums. One is a storage building with a single envelope and heating only. The other storage building consists of a box-in-a-box construction with full HVAC control. The third is an exhibition building with full HVAC.
Only 20 museums were used for data analysis, Museum 3 is left out because of non-continuous data due to a malfunctioning data logger.

Figure 2.2 displays the museums matrix with all measured museums placed in it. Also the number of rooms being measured are displayed. When looking at figure 2.2, the first thing that can be noticed is that few museums have a number for the LoC that is lower than the number for QoE. In other words: few museums are located above the diagonal: only M17. This new museum and storage building has a heating system only; RH is not modified. One of the causes of this uneven distribution is that the emphasis used to be on systems when a museum was improved, often because the building could not be modified due to the monumental status.



Quality of Envelope	1	2	3	4
4	X	M17 rooms: 7 surfaces: 3	X	M18 rooms: 7 surfaces: 9 M21 rooms: 22 surfaces: 12
3	X	X	X	M12 rooms: 20 surfaces: 3
2	X	M04 rooms: 5 surfaces: 3 M11 rooms: 12 surfaces: 0 M14 rooms: 9 surfaces: 4	M04 rooms: 4 surfaces: 2	M07 rooms: 15 surfaces: 0 M10 rooms: 12 surfaces: 0 M14 rooms: 4 surfaces: 1 M19 rooms: 9 surfaces: 0
1	M02 rooms: 15 surfaces: 0 M05 rooms: 5 surfaces: 5 M08 rooms: 16 surfaces: 7 M09 rooms: 5 surfaces: 3	M01 rooms: 2 surfaces: 0 M02 rooms: 2 surfaces: 0 M05 rooms: 3 surfaces: 3 M06 rooms: 13 surfaces: 0 M08 rooms: 1 surfaces: 0 M09 rooms: 3 surfaces: 1 M16 rooms: 17 surfaces: 7 M20 rooms: 9 surfaces: 7	M01 rooms: 5 surfaces: 0 M13 rooms: 5 surfaces: 0	M15 rooms: 14 surfaces: 12
	1	2 Level of Control	3	4

Figure 2.2: Museum classification matrix, combinations of QoE and LoC.

The second remark is that there are a lot of monuments that still have their original envelope without any changes to improve its physical aspects. The LoC ranges from 1 to 4; very different setups and systems are used.
As a third remark it is noted that full HVAC systems are applied to any kind of buildings. Even in QoE 1, in which a full HVAC system is questionable because of massive energy use and less satisfactory results, this system is still applied.

2.3. CASE STUDY SETUP

All 21 museums were researched using the same method in order to be able to compare the measured data in all cases. This method consists of the following steps:

- Quick scan
- Inventory
- Measurements
- Modeling
- Recommendations

2.3.1. Quick scan

A quick scan is used to get acquainted with the building. A member of the technical staff or a conservator shows the building, the climate systems and the collection while discussing recent problems he or she experienced. Also some initial measurements are carried out during this tour. Infrared thermal imaging is used to pinpoint thermal bridges and to assess temperature distribution on walls and collection objects. This gives an impression of the balance between average room climates and local climates. Also some temperature and humidity measurements are performed to check differences between various measurement positions. This is helpful in the measurement setup, as described hereafter.

The quick scan also is used to make a first guess on the building type (QoE) and system type (LoC). This is important, because it determines the position in the museums matrix.

2.3.2. Inventory

The inventory is a very important aspect of the study. The buildup of the museum is needed. This includes floor plans, construction drawings, sections and elevations and also the printed specifications of building and climate system. The parts that are not on paper need to be checked in the actual situation.

Next to these properties also the use of the museum is important to take into account. Visitors are guided through the building in groups or are allowed to freely wander around. The amount of visitors per year and the average visit length is important for estimating internal heat and moisture gains. Also the type of objects on display (originals or replicas?), the positions of the objects and extra preventive measures are noted.

Another aspect is the control of the climate system. The position of sensors, the layout of software in the building management system, set points for temperature and humidity etc. are needed to reproduce the indoor climate using a computer model.

Finally building use during the measurement period is important. Special events, e.g. evening openings, temporary exhibitions and system malfunctions, are recorded in a logbook.

2.3.3. Measurements

Two types of measurements have been performed: continuous and periodic measurements.

Continuous measurements

Continuous measurements on air temperature, relative humidity and in some cases also surface temperature are executed by a combined sensor. This sensor contains a transmitter that sends the measured data to a wireless data logger that is placed centrally in the building [Eltek, 2010]. The function of the logger is to temporarily store the data with a preset interval of, in most cases, 10 minutes. A GSM connection is used to download data from the logger to a central server at the university. This server processes these data into a database and makes the data available to the museum staff by means of an Internet application.

Figure 2.3: Permanent measurement equipment: Eltek datalogger, 10 Eltek T and RH transmitters, 1 Eltek mV transmitter, 1 Maestro GSM modem and a surface temperature sensor (to connect to a transmitter).

The number of measurement positions ranges from 5 to 50 per museum. A period of at least one year is measured continuously. Table 2.4 provides an overview. Regularly the placement of sensors is checked to make sure that the current position is equal to the initial position. If a sensor is moved, no matter the reason, the data cannot be used.

To check the accuracy of these temperature and humidity sensors, the transmitters are calibrated prior to and after the measurement. This is done by comparing the measurement results of the sensors to a very precise reference sensor – calibrated by the NMI (NL: Nederlands Meetinstituut) – of which the uncertainty is known. Under normalized circumstances the sensors and the reference sensor results are compared by applying a temperature and humidity trajectory in a special climate chamber. The relation between the sensor and the reference is transferred into a polynomial function containing calibration constants. This function is used when transferring measurement data from logger into database.

After calibration, the overall accuracy for temperature is in between 0.1 and 0.2°C and for RH in between 0.8 and 1.4%RH; this is slightly better than the accuracy provided by the manufacturer [Sensirion, 2010]. See appendix A for more details regarding the sensors used and the calibration of one sensor as an example.

Table 2.4: Permanent measurements in 21 museums: start date, end date, interval time and institution.

MUSEUM	START DATE [year month day]	END DATE [year month day]	INTERVAL [minutes]	Measured by
M01	2005 01 24	2006 01 23	30	ICN
M02	2004 01 01	2004 12 31	30	ICN
M03	2008 09 15	2009 09 14	10	TU/e
M04	2008 01 10	2009 01 09	10	TU/e
M05	2004 01 01	2004 12 31	15	TU/e
M06	2002 02 08	2003 02 07	30	ICN
M07	2008 01 01	2008 12 31	10	TU/e
M08	2008 01 01	2008 12 31	20	TU/e
M09	2008 01 01	2008 12 31	10	TU/e
M10	2007 04 17	2008 04 16	15	TU/e
M11	2008 04 23	2009 02 02	30	ICN
M12	2009 01 01	2009 12 31	10	TU/e
M13	2007 04 23	2008 04 22	15	TU/e
M14	2006 12 10	2007 12 09	15	TU/e
M15	2008 12 01	2009 11 30	10	TU/e
M16	2008 04 01	2009 03 31	10	TU/e
M17	2008 01 01	2008 12 31	10	TU/e
M18	2008 01 01	2008 12 31	15	TU/e
M19	2007 01 01	2007 12 31	15	TU/e
M20	2008 04 01	2009 03 31	10	TU/e
M21	2008 01 01	2008 12 31	10	TU/e

Pinpointing sensors is done in accordance with the museum staff. Infrared thermal imaging (see figure 2.4) is used to get a global impression of the conditions in a room; it is decided where to measure surface and air temperature and RH. Sensors are placed in such a way that museum visitors cannot touch them. In case the sensor is clearly visible (e.g. in a display case) a card is placed near the sensor to explain its function.

For each position it is clearly marked whether it concerns:

1. An exhibition room;
2. A display case;
3. A storage area;
4. A staff room;
5. A surface mounted position or
6. A climate system related position.

This is important for the analysis of the measurement data (see chapter 4 and 6); in appendix B these positions are included in the table under PT (Position Type).

Periodic measurements

Periodic measurements are measurements that are carried out once or seasonally. They consist of infiltration rate measurement, flow rates and infrared thermal imaging.

Ventilation rate measurements are performed by measuring the concentration of a tracer gas in the indoor air volume. This concentration is practically zero in the initial situation. Tracer gas is released into the volume, thus leading to a certain concentration. This concentration will gradually drop to zero, as fresh outdoor air enters the volume and replaces the indoor air. The speed of this decay in concentration is a measure for the infiltration rate. This is one of several ventilation rate measurements that are possible [Grieve, 1990] [Nijenmanting, 2009].

Flow rates are measured to determine the volume of air distributed into a zone per unit of time. A so-called FlowFinder is used to place over an air inlet grid. This device measures the pressure difference between air inlet and the apparatus, and it applies a flow using an internal fan. Controlling the flow to keep the pressure difference at zero implies that inlet air flow and internal fan flow are equal. The volume rate of air is indicated by the apparatus [Acin, 2008].

Infrared thermal imaging is used to trace a surface temperature that differs from the surrounding surface temperatures. A thermal camera is able to predict surface temperatures by measuring infrared radiation. Differences in emissivity and reflections may hinder a correct prediction [FLIR, 2006]. The camera creates a digital full color image displaying different temperatures in a range of colors (see figure 2.4, left). By measuring the absolute humidity of the air, a thermal image can easily be converted into a hygric image (figure 2.4, right) [Schellen, 2002]. In figure 2.4 an example is given of a museum wall with paintings. Part of the wall is cold; the paintings are placed at a short distance in front of the wall. The RH of the inner wall, floor and paintings is about 50%RH. Near the cold spots 58%RH is encountered.

2.3.4. Simulation

Modeling and simulating the indoor climate in a museum is done by using HAMbase [de Wit, 2007]. The parameters that originated from the inventory are used to set up a computer model which contains the physical aspects that are of influence on temperature, humidity and air flow.

An important aspect of using a model is validation. By simulating the same period as the period measured and comparing simulation and measurement, the quality of the model is assessed. It is impossible to exactly match the measured data using a model, because a model is a simplified version of the complex reality. It is, however, important that average yearly temperatures and RH values match and that seasonal, weekly, daily and hourly changes are in accordance with the measurements.

A validated model is suitable to investigate the influence of changes made to either building, system, set points or use on the indoor climate. Chapter 7 will go deeper into using a model to assess changes.

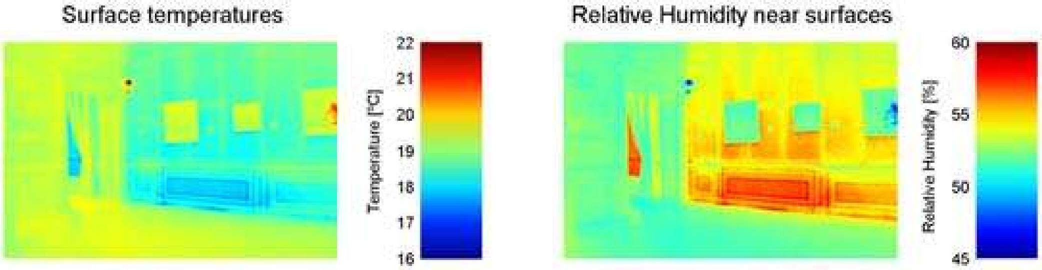


Figure 2.4: Periodic measurement: infrared thermal image (left) and calculated infrared hygric image (right).

2.3.5. Reporting to each museum

Of each museum an overview is given of the current indoor climate and the current risks for conservation of objects. Also recommendations are made to improve conservation. In some cases very simple measures can reduce risks considerably, e.g. placing a delicate object in another room or changing the winter set point from 20 to 19°C. In some cases more dramatic measures are needed, like installing screens to reduce solar radiation or installing a humidifier. These reports are available for each individual museum and are confidential. The indoor climate is of major importance when a museum wishes to borrow objects from other museums: most museums like to keep their climate secret so they do not necessarily need to be honest about their indoor climate.

2.4. ANALYSIS TOOLS

Permanent measurements and results from computer simulation studies as described in the previous paragraph generate a series of temperatures and relative humidities. Analyzing these series can be difficult because of the large amount of data. In order to make the analysis easier, the Climate Evaluation Chart is introduced [Martens et al., 2006 and Schijndel, van et al., 2006].

2.4.1. Climate Evaluation Chart

Within this PhD study, the Climate Evaluation Chart (CEC) was developed to simplify the interpretation of temperature and humidity data [Martens et al., 2006] [Schijndel et al., 2006]. The basis of a CEC is formed by a psychrometric chart, in which the data is plotted. An example of a CEC is displayed in figure 2.5. Only the interpretation of the chart is explained; the data itself are not important at this moment.

The background of the chart is a standard psychrometric chart for air, with on the horizontal axis humidity mixing ratio in g/kg (the number of grams of moisture for each kilogram of dry air); on the vertical axis dry bulb temperature in °C and curves for the relative humidity in %. Warm air can contain more moisture than cold air, so the maximum humidity ratio increases for an increasing temperature. This is indicated e.g. by the 100% relative humidity curve. For each temperature, this maximum is divided into 10 equally spaced parts, displayed by the 10% up to the 90% RH lines.

For low temperatures, the humidity mixing ratio has a large influence on RH while for high temperatures this influence is smaller.

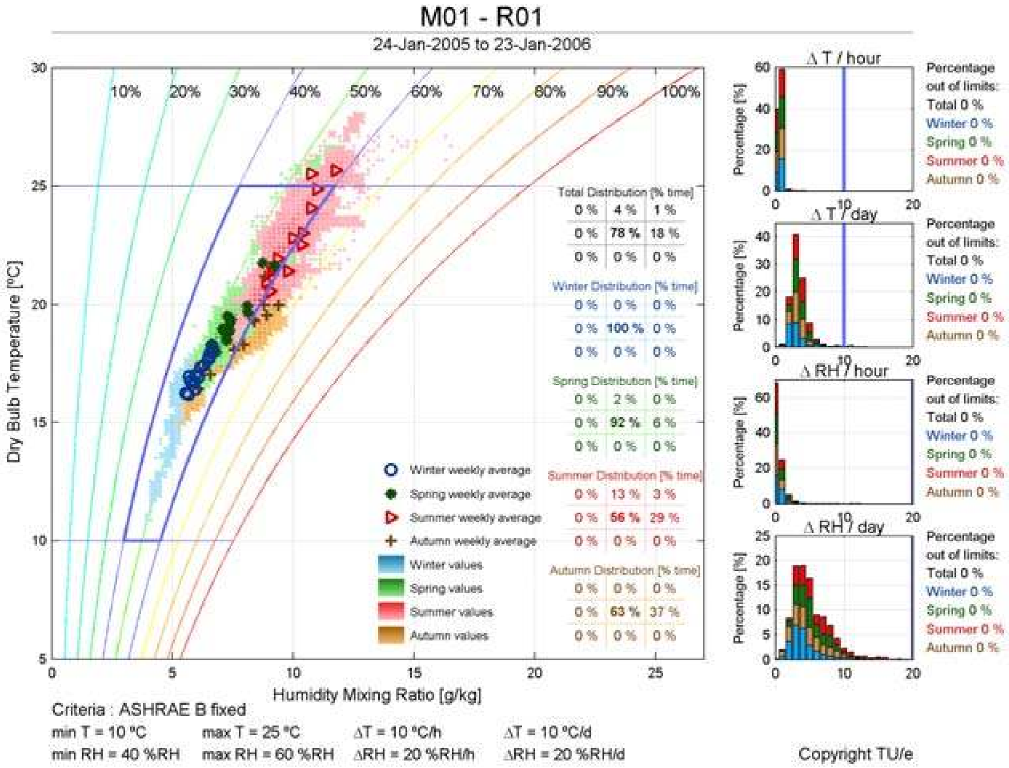


Figure 2.5: Example of a Climate Evaluation Chart.

The indoor climate is presented by seasonal colors (winter from December 21 till March 21 in blue, spring from March 21 till June 21 in green, summer from June 21 till September 21 in red and autumn from September 21 till December 21 in brown). The intensity of each color represents the percentage of time of occurrence; all measured or simulated data values are displayed. Also seasonal weekly averages are displayed using symbols (o, *, > and +). The colors visualize the indoor climate distribution over the seasons. For example, a very stable indoor climate produces a narrow spot, in contradiction to a free floating climate which produces a large 'cloud' of data entries.

Also 2 horizontal blue lines and 2 blue curves are displayed in the psychrometric chart. These represent the performance guideline the indoor climate is compared to. Below the chart criteria for this performance guideline are presented: minimum and maximum temperature and relative humidity (min T, max T, min RH and max RH) and indoor climate change rate boundaries: maximum allowed hourly and daily changes in temperatures and relative humidities (ΔT/hour, ΔT/day, ΔRH/hour and ΔRH/day).

The guideline divides the psychometric chart into 9 parts: a 3-by-3 matrix. This division is also displayed for the total distribution and distribution per season, on the right in the psychrometric chart. The meaning of each part is as follows:

Too dry and too hot T > Tmax, guideline RH < RHmin, guideline	**Too hot** T > Tmax, guideline RHmin, guideline ≤ RH ≤ RHmax, guideline	**Too humid and too hot** T > Tmax, guideline RH > RHmax, guideline
Too dry Tmin, guideline ≤ T ≤ Tmax, guideline RH < RHmin, guideline	**OK** Tmin, guideline ≤ T ≤ Tmax, guideline RHmin, guideline ≤ RH ≤ RHmax, guideline	**Too humid** Tmin, guideline ≤ T ≤ Tmax, guideline RH > RHmax, guideline
Too dry and too cold T < Tmin, guideline RH < RHmin, guideline	**Too cold** T < Tmin, guideline RHmin, guideline ≤ RH ≤ RHmax, guideline	**Too humid and too cold** T < Tmin, guideline RH > RHmax, guideline

Next to the psychrometric chart 4 small graphs are displayed that show the calculated climate change rates: hourly and daily changes in temperature and hourly and daily changes in relative humidity respectively. Also here the guideline is displayed in blue; percentages of exceedance are given.

The CEC is helpful in determining if and when a climate guideline is exceeded. Only guidelines with fixed boundaries can be used; seasonal changes cannot be taken into account (except when a separate CEC is created for each season). When some measured values are out of the desired area there usually is no real reason for concern. Weekly averages out of the target area ask for some further analysis to pinpoint the cause. The histograms on the right help in assessing fluctuations in indoor climate.

2.4.2. Website www.monumenten.bwk.tue.nl

Within this PhD study a website (see figure 2.7) has been created as a service for the staff of the museums under research. Various climate analysis tools are available online. After logging in, the employees of each museum can select the period to display and the type of graph.

2.5. THE DUTCH WEATHER

This paragraph provides information about the Dutch climate. Figure 2.6 shows in which period permanent measurements were performed in each museum. For most museums, the year 2008 has been measured. A CEC of 2008 is displayed in figure 2.8. The Netherlands has a tempered sea climate without a dry period. Weekly average temperatures range in between -5 and 21°C. The relative humidity is usually high: in all seasons most measured values are higher than 70%. Occasionally the RH drops to lower values of about 20%.

Table 2.5 and figure 2.9 show differences between all years in which measurements were carried out.

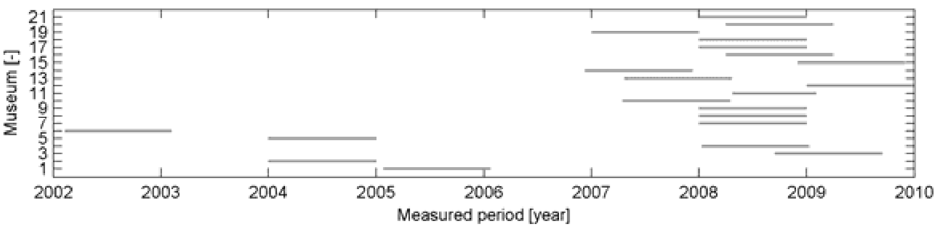


Figure 2.6: Measured period per museum.

Table 2.5: Parameters of the Dutch weather during 2002, 2004, 2005, 2007, 2008 & 2009, data from KNMI.

	2002	**2004**	**2005**	**2007**	**2008**	**2009**
Annual mean temperature [ºC]	10.8	10.4	10.7	11.2	10.6	10.5
Minimum temperature [ºC]	-8.6	-7.4	-14.0	-6.6	-8.6	-11.1
Maximum temperature [ºC]	32.9	32.0	32.7	31.4	30.7	33.8
Annual mean relative humidity [%]	82.6	82.0	82.0	82.2	81.2	80.5
Minimum relative humidity [%]	26	26	28	19	23	28
Maximum relative humidity [%]	100	100	100	100	100	99
Number of tropical days (Tmax > 30ºC)	4	2	3	1	1	1
Number of summer days (Tmax > 25ºC)	14	25	29	18	23	20
Number of warm days (Tmax > 20ºC)	84	77	82	87	86	89
Number of frost days (Tmin < 0ºC)	38	59	48	34	52	54
Number of ice days (Tmax < 0ºC)	8	3	5	3	3	9

Table 2.5 shows that from all years measured, the year 2007 has the highest annual mean temperature. The number of tropical days – days in which the maximum temperature is equal to or over 30ºC – is highest in 2002: 4 days. The year 2004 has the lowest average temperature (10.4ºC) and also the least warm days – days in which the maximum temperature is equal to or over 20ºC – just 77 while the other years show 82 to 89 days. The lowest temperatures are recorded in 2005 (-14.0ºC) and 2009 (-11.1ºC). The highest number of ice days – days in which temperature remains lower than 0ºC all day – is 9 for 2009 and 8 for 2002.

Relative humidity shows little difference in the years measured. The annual mean RH is in between 80.5 and 82.6%. Minimum RH values range from 19 to 28%, while the maximum value is 99 or 100%.

Although the measured period for the 21 museums is not similar, measured results can be compared because the weather in 2002, 2004, 2005, 2007, 2008 and 2009 is more or less similar. Moreover, the sites slightly differ in location, which also results in small differences in weather.

Welcome to Physics of Monuments!

Welcome to the new Internet site 'Physics of Monuments', one of the competence areas of the TU Eindhoven. We do research on all kinds of heat and moisture related subjects in monumental buildings. The analysis of drawings and installations, climate measurements and the creation and validation of simulation models belong to our main activities. Several monumental buildings have already been examined, in The Netherlands and abroad. The monitoring of the indoor climate in many Dutch museums is carried out.

Mission

The general mission is the conservation of the cultural heritage by giving specific climate recommendations. Our competences are:

- monitoring the indoor climate, all results are available on the website
- assessing indoor climate parameters, such as temperature, relative humidity, lighting level and carbon dioxide concentration
- analysing buildings using infrared imaging
- setting up simulation models of heat, air and moisture related issues.

Clients

Most of our clients are owners of museums, monuments and churches. If you have a problem that lies within our competence area and within the research objective of the TU/e, you can contact us. We use modern tools to do research and to give well-supported recommendations.

Figure 2.7: Website www.monumenten.bwk.tue.nl.

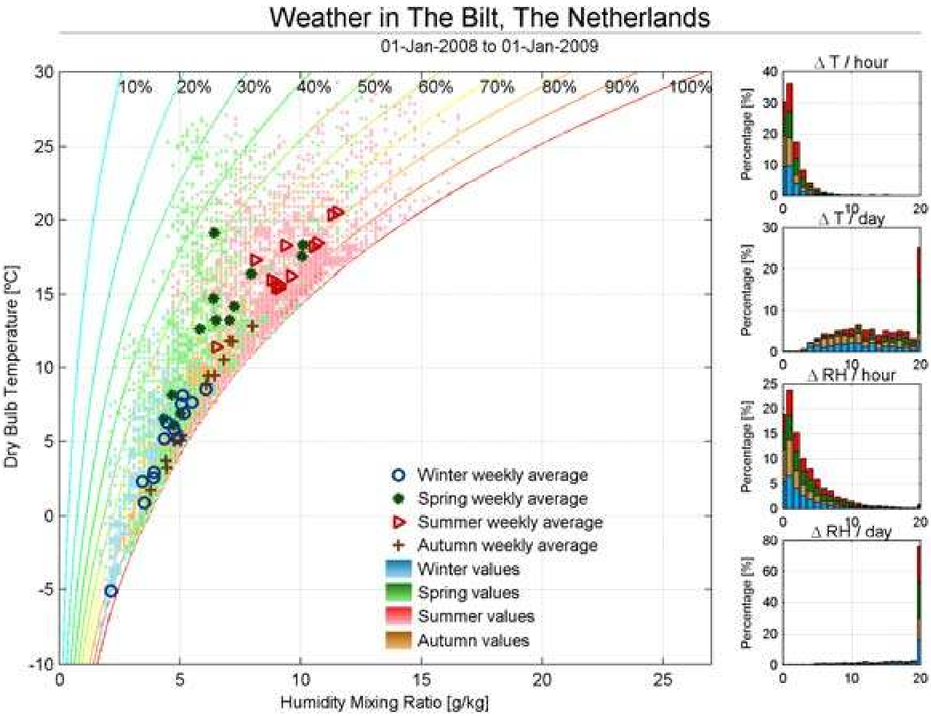


Figure 2.8: CEC of the Dutch weather during 2008, data from KNMI.

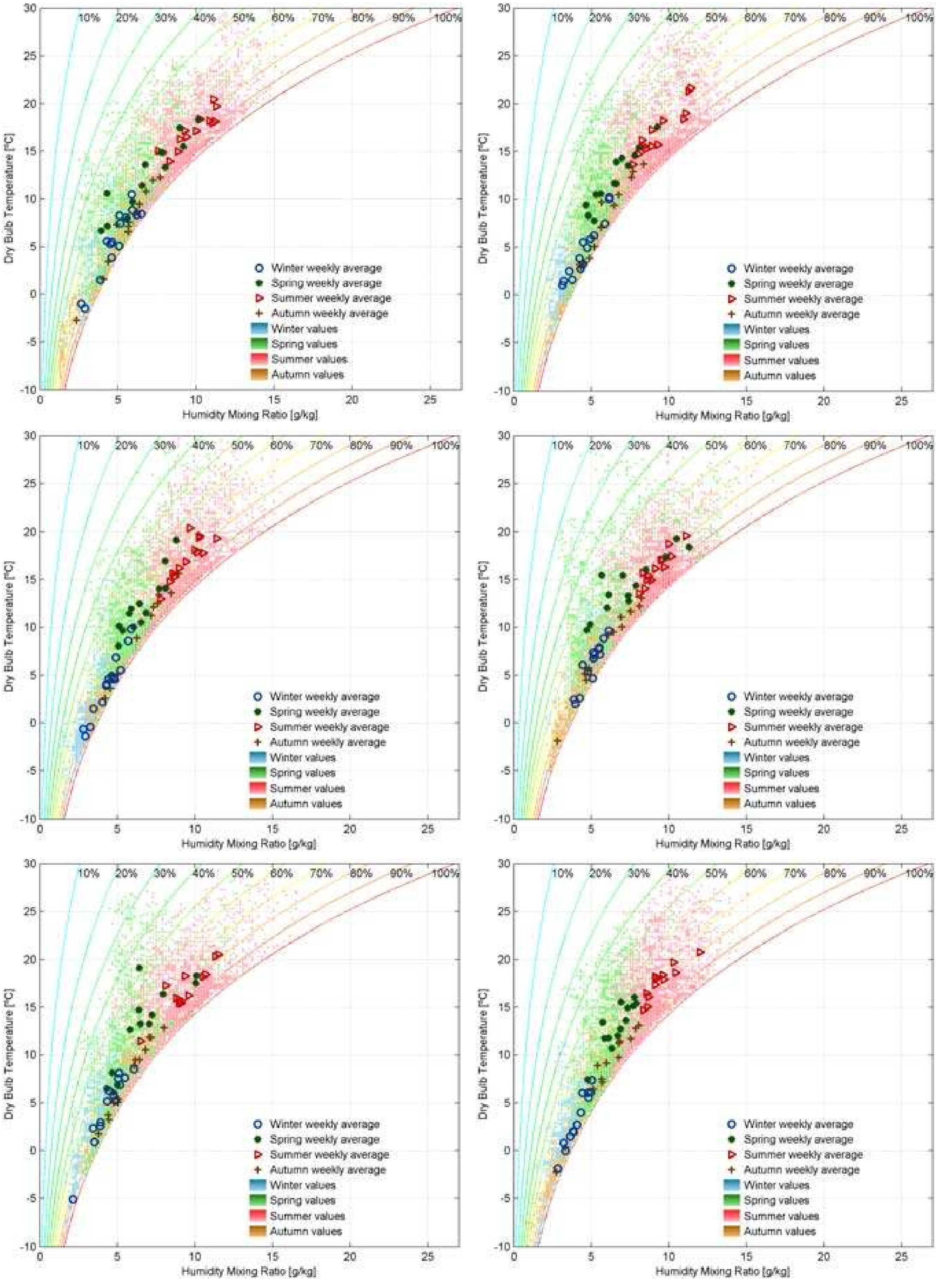


Figure 2.9: CEC of the Dutch weather during 2002 (top left), 2004 (top right), 2005 (center left), 2007 (center right), 2008 (bottom left) and 2009 (bottom right), data from KNMI.

General climate risk assessment 3

In this chapter, a general climate risk assessment method is introduced, which determines how indoor climates fit into the ASHRAE climate classes.

In the introduction a literature review is presented on characterizing and comparing different climates. The general risk assessment method is introduced and discussed in paragraph 3.2. As an example, this method is used to asses the indoor climate in one room and in one museum; results are displayed and discussed in paragraph 3.3. The last paragraph states the advantages and disadvantages of the method.

3.1. INTRODUCTION

Museums worldwide try to establish a safe indoor climate suitable for preservation of objects on display. But even though they share the same goal, a lot of different climates exist in these museums; the climate shows gradients and fluctuations with varying amplitude and frequency around average values that vary from place to place. Mapping these climates is useful in order to i) compare different zones in museums, ii) compare different types of museum buildings, climate systems and their performance and iii) determine the quality of the climate the objects are exposed to. If the indoor climate quality is regarded as (part of) the risk (probability to loss of value) to collections – e.g. by assessing dimensional changes in materials as a result of the climate – a direct link is established between environmental factors and material degradation. It is obvious that climates can be very different while posing the same risk to collections.

It is important to note that: i) collections consist of various sub-collections; ii) every sub-collection consists of different objects; iii) objects consist of several materials and constructions. Climates that have a high preservation quality for one type of object or material might be damaging to other types.

Analyzing climates is a fairly old subject. Back in 1884 Köppen introduced a systematic approach to specify the different climates on Earth. Each climate is described by yearly and monthly averaged temperatures and precipitation. The main difference between classes is based on natural vegetation; each class has its own kind of plants and trees. Köppen kept refining his system over the years [Köppen, 1936].

It is important to note that, by specifying ranges for both temperature and the amount of rainfall and linking this to the natural vegetation type, Köppen's system is able to predict vegetation type by processing climate measurements. A similar approach is used in museum indoor climate guidelines: by specifying ranges for climate parameters – e.g. temperature and relative humidity – and linking these to risks on damage to objects the climate's effect on the preservation of museum objects can be predicted.

The most important design guidelines currently used in museums are based on the ASHRAE climate classes [ASHRAE, 2011]. The American Society of Heating, Refrigeration and Air-conditioning Engineers came up with guidelines for the design of climate systems in museums. Some major North American institutions, e.g. the Smithsonian, were involved in specifying these guidelines. This climate guideline first appeared in North America in 1999. Nowadays the guidelines are also used in other regions in the world; in the Netherlands it became standardized in 2008 [Ankersmit, 2009]. The first part of this introduction introduces the ASHRAE climate classes and explains their background. The underlying argument for classification of climates is risk of degradation: biological, mechanical and chemical. Each one of these is looked into in more detail in the second part of this introduction.

3.1.1. ASHRAE climate classes

For museum climates the main design guideline is the ASHRAE museum climate table [ASHRAE, 2007]. Several classes are given which relate to certain ranges in temperature and relative humidity. It must be noted that an ideal indoor climate does not exist; the table couples a climate type to the risks and benefits this climate poses to the collection. These classes help designers to fit a proper climate into a building, but they also help non-designers, because they provide a few clearly distinguishable climates when looking into the risks and benefits for mixed collections. A copy of the main ASHRAE table is given in table 3.1. The right column in table 3.1 states the risks and benefits for collections.

The most optimal climate – the climate that causes the least mechanical damage for most objects – according to ASHRAE is climate class AA. This climate allows a short temperature fluctuation (shorter than seasonal) of plus or minus 2K around a yearly average temperature. For the relative humidity the maximum allowable fluctuation is plus or minus 5% around a yearly average. Seasonal temperature changes are allowed as long as these changes remain in the plus or minus 5K range.
The mechanical risks for the collection are negligible. Chemically unstable objects will still deteriorate. Also objects are at risk that can't cope with a relative humidity around the annual average.

Class A is the second best climate class. This class is divided into two sub-classes. The first is similar to AA but allows a seasonal change in relative humidity of 10%. In this dissertation it is called 'As', in which the s stands for seasonal RH change. The second does not allow a seasonal change but the short fluctuations in RH are larger (10 instead of 5%). It is referred to as A in this dissertation. The difference between the two has to do with relaxation: objects adapt to slow (e.g. seasonal) changes in RH – they come into equilibrium with it and stresses caused by this change decrease slowly – and therefore objects are less vulnerable. A long fluctuation of plus or minus 10% poses the same risk as a shorter fluctuation of plus or minus 5% [ASHRAE, 2007].
Classes A and As both pose a small mechanical risk to highly vulnerable objects, but all other objects are safe unless they are chemically unstable.

In Class B both seasonal change and higher short fluctuation in RH are tolerated; temperature is allowed to fluctuate 5K over time and place (gradients), while the short RH fluctuations need to be below 10%. The seasonal adjustment in RH is 10% up and down and temperature may rise 10K or drop to a low value to stay within the proper RH range. There is a moderate risk of mechanical damage to highly vulnerable objects, a tiny risk to most paintings and photographs but no risk to most other objects. Chemically unstable objects benefit from the allowed winter setback.

Table 3.1: Museum climate guidelines according to ASHRAE [ASHRAE, 2007]

<table>
<tr><th rowspan="2">Type</th><th rowspan="2">Set point or annual value</th><th colspan="3">Maximum Fluctuations and Gradients in Controlled Spaces</th><th rowspan="2">Collection Risks and Benefits</th></tr>
<tr><th>Class of control</th><th>Short fluctuations & space gradients</th><th>Seasonal adjustments in system set point</th></tr>
<tr><td rowspan="6">General Museums, Art Galleries, Libraries and Archives
All reading and retrieval rooms, rooms for storing chemically stable collections, especially if mechanically medium to high vulnerability</td><td rowspan="6">50%RH (or historic annual average for permanent collections)
Temperature set between 15 and 25°C
Note: rooms intended for loan exhibitions must handle set point specified in load agreement, typically 50%RH, 21°C but sometimes 55 or 60%RH</td><td>AA
Precision control; no seasonal RH changes</td><td>±5%RH, ±2K</td><td>Relative humidity no change, Up 5K; down 5K</td><td>No risk of mechanical damage to most artifacts and paintings. Some metals and minerals may degrade if 50%RH exceeds a critical relative humidity. Chemically unstable objects unusable within decades.</td></tr>
<tr><td rowspan="2">A
Precision control; some gradients or seasonal changes, not both</td><td>As
±5%RH, ±2K</td><td>Up 10%RH; down 10%RH; Up 5K, down 10K</td><td rowspan="2">Small risk of mechanical damage to high vulnerability artifacts; no mechanical risk to most artifacts, paintings, photographs, and books. Chemically unstable objects unusable within decades.</td></tr>
<tr><td>A
±10%RH, ±2K</td><td>RH no change; Up 5K, down 10K</td></tr>
<tr><td>B
Precision control; some gradients plus winter temperature setback</td><td>±10%RH, ±5K</td><td>Up 10%RH, down 10%RH; Up 10K but not above 30°C, down as low as necessary to maintain RH control</td><td>Moderate risk of mechanical damage to high vulnerability artifacts; tiny risk to most paintings, most photographs, some artifacts, some books; no risk to many artifacts and most books. Chemically unstable objects unusable within decades, less if routinely at 30°C, but cold winter periods double life.</td></tr>
<tr><td>C
Prevent all high risk extremes</td><td colspan="2">Within 25 to 75%RH year-round
Temperature rarely over 30°C, usually below 25°C</td><td>High risk of mechanical damage to high vulnerability artifacts; moderate risk to most paintings, most photographs, some artifacts, some books; tiny risk to many artifacts and most books. Chemically unstable objects unusable within decades, less if routinely at 30°C, but cold winter periods double life.</td></tr>
<tr><td>D
Prevent dampness</td><td colspan="2">Reliably below 75%RH</td><td>High risk of sudden or cumulative mechanical damage to most artifacts and paintings because of low-humidity fracture; but avoids high-humidity delamination and deformations, especially in veneers, paintings, paper, and photographs. Mold growth and rapid corrosion avoided. Chemically unstable objects unusable within decades, less if routinely at 30°C, but cold winter periods double life.</td></tr>
<tr><td rowspan="2">Archives, Libraries
Storing chemically unstable collections</td><td>Cold store: -20°C, 40%RH</td><td colspan="3">±10%RH, ±2K</td><td>Chemically unstable objects usable for millennia. Relative humidity fluctuations under one month do not affect most properly packaged records at these temperatures (time out of storage becomes lifetime determinant).</td></tr>
<tr><td>Cool store: 10°C, 30 to 50%RH</td><td colspan="3">(Even if achieved only during winter setback, this is a net advantage to such collections, as long as damp is not incurred)</td><td>Chemically unstable objects usable for a century or more. Such books and papers tend to have low mechanical vulnerability to fluctuations.</td></tr>
<tr><td>Special metal collections</td><td>Dry room: 0 to 30%</td><td colspan="3">Relative humidity not to exceed some critical value, typically 30%RH</td><td></td></tr>
</table>

Class C does not have any temperature limits. The relative humidity is limited to 25% on the lower end to prevent dehydration of objects and to 75% on the higher end to prevent fungal growth and other risks that involve changing of material properties at high RH values. The risks associated with class C are high risk of mechanical damage to highly vulnerable objects, a moderate mechanical risk to most paintings and photographs and to some books and artifacts and a tiny mechanical risk to most artifacts and some books. Chemically unstable objects also benefit from lower temperature set points during the winter period.

Class D only prevents damp conditions; relative humidity over 75% is avoided. This provides a high risk on cumulative or sudden fracture due to low humidity for most artifacts and paintings. It avoids risks due to high humidity. Also molding and rapid corrosion are avoided.

Three other classes are described that are common in museum storage areas. These classes mainly address chemically unstable objects. The Cold class is meant especially for chemically unstable objects. These objects remain intact for millennia when preserved according to the standards indicated in this class. At these low temperatures short relative humidity fluctuations do not affect these objects. The Cool class increases the life of chemically unstable objects to about a century. Also these cooled objects show a low vulnerability to mechanical damage. For metals a dry class is introduced that keeps the relative humidity below 30% in order to slow down or stop oxidation processes.

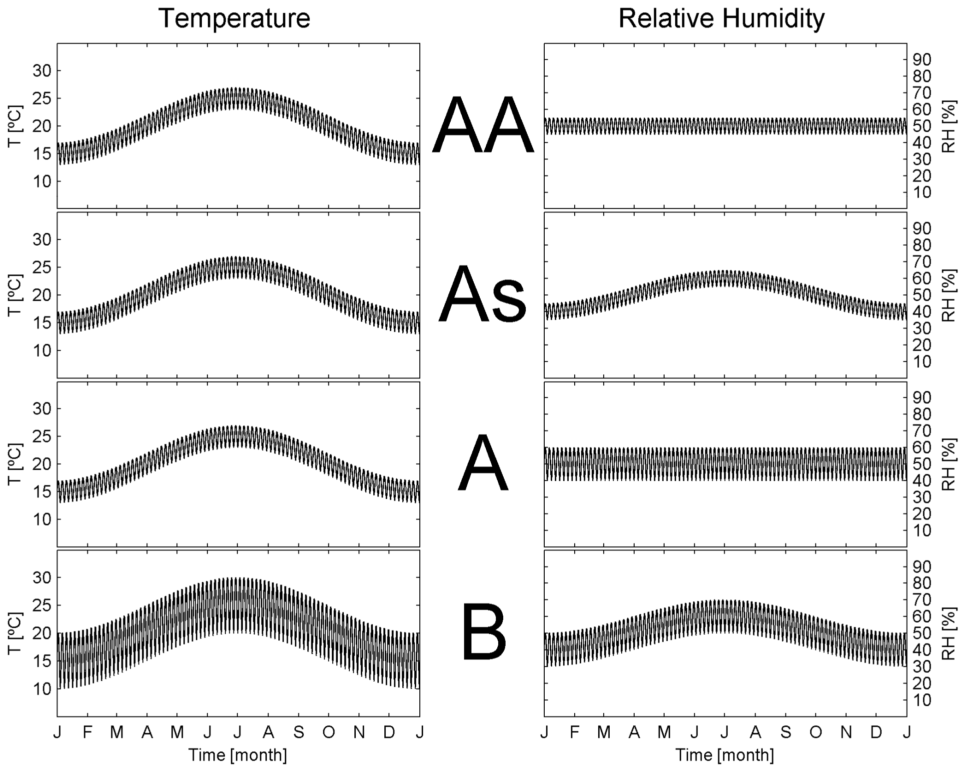


Figure 3.1: Example of the ASHRAE climate classes. AA, As and A show a short temperature fluctuation of 2K; for B this is 5K. AA and A do not allow a seasonal RH adjustment. AA and As allow short changes in RH of 5%, while A and B allow 10%.

Figure 3.1 displays an example of the ASHRAE classes AA up to B with a 5K seasonal change and maximum allowed short term changes. Yearly averages are 15°C and 50%RH; for both seasonal and daily changes sine curves are used.

3.1.2. Three degradation principles

As mentioned before, temperature and relative humidity may lead to three types of degradation. The first – biological degradation – occurs when temperature and relative humidity are in the growth range of fungi. The second – mechanical degradation – is related to changes in relative humidity (and temperature to a lesser extent), which cause materials to shrink and expand. The third – chemical damage – is associated with reaction speed of chemical processes which is influenced by temperature and humidity. In this paragraph each degradation principle is discussed in more detail.

Biological degradation

Fungal growth is the cause for many degradation processes in museums across the world. High relative humidity near surfaces is a necessary condition for fungi to appear. Michalski [1993] concluded that a room RH of 60% or less prevents all mould growth, while 75% or higher presents a real danger. Especially the 60% value seems low; Scott [1994] concluded that mould growth in tropic regions did not occur as often as was expected. This makes sense since cold surfaces – at which the RH is much higher than the room RH – simply do not exist in tropic regions except in air conditioned buildings. Scott also advised to use thorough air circulation to prevent stagnant air, a cause for localized climates (so-called microclimates).

Although fungal growth is often related to surface condensation, Adan [1994] stated that experiments show that fungi can germinate at relative humidities below 100%; even optimum growth conditions are below 100%. Moreover, fungi are capable of fast water absorption when the RH increases, so short periods of high RH should not be neglected.

At the surface of building materials, Adan continues, RH hardly differs from air RH very close to the surface; the air humidity mixing ratio and surface temperature determine the RH. The RH close to the surface is used to predict the fungal growth. He introduced Time-Of-Wetness (TOW) as a measure to predict fungal growth. TOW is defined as the period the RH is over 80% divided by the length of the total period. This period is considered to be cyclic; in most experiments a daily cycle is used. For a TOW below 0.5, fungal growth is negligible.

The TOW, determined close to a surface, is a better fungal growth prediction tool than the 60% room condition stated by Michalski, because it takes into account both building and local microclimates. As can be seen in chapter 4, conditions close to the building envelope differ much from conditions elsewhere in the building.

Based on published data, Clarke [1996] defined growth limit curves for six generic mould categories in terms of the minimum combination of temperature and relative humidity required to sustain growth on indoor building surfaces; an equation is given which is used as a lower limit. The result is a design tool which can predict the likelihood of mould growth. The influence of temperature on fungal growth is taken into account. By incorporating more than one type of fungi in the model the estimate is more accurate. Still one part is missing for a proper analysis of fungal growth: the availability of nutrients. According to Sedlbauer [2001] the substrate material plays an important role in determining fungal growth conditions. A model is presented that combines temperature, RH, germination time and growth rate on different substrate types. Temperature, humidity and substrate have to be available simultaneously over a certain period of time in order to trigger fungal growth. This is currently the most extensive model available. Figure 3.2 displays this so-called isopleths system: a combination of 4 graphs that determine whether fungal growth can occur and at which growth rate. The germination time is displayed in the left graphs: the time needed for spores to become active for combinations of temperature and humidity is given. Lines of equal germination time – isolines – are plotted; also a minimum is given which is marked LIM. The right graphs display growth rates for combinations of temperature and humidity. Also isolines are given that connect equal rates. The top graphs are valid for surface material type I: biologically recyclable material. The bottom graphs correspond to type II: non-biologically recyclable materials which have a porous structure. Type I acts as a nutrient for the fungi directly, while type II is able to capture dust and other particles that function as a nutrient.

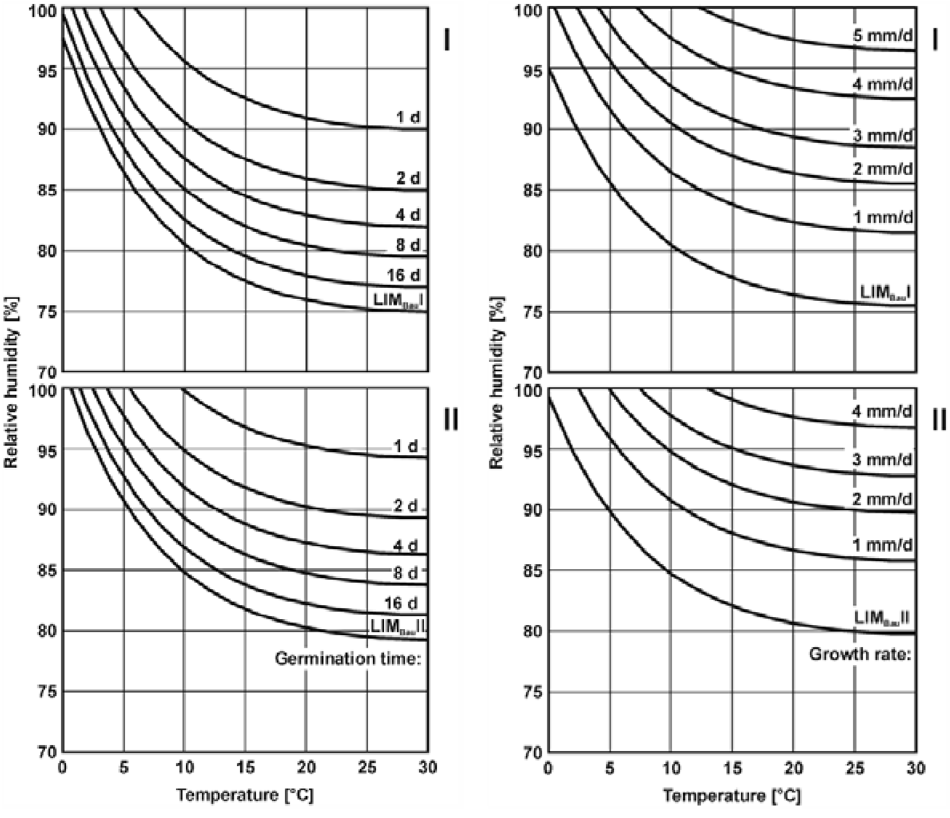


Figure 3.2: Spore germination time (left) and mycelium growth rate (right) for material category I (biologically recyclable materials) and II (materials with porous structure) [Sedlbauer, 2001].

The model is used according to the following setup: once the condition near a surface of type I or II is over the lower germination limit, spores slowly become active fungi. This takes time, which is displayed in the left graph: higher temperatures and higher RH values reduce germination time. Once the fungi become active, growth occurs at a speed corresponding to the right graph. When conditions over the limiting curve do not last long enough to lead to germination this process stops.

According to Sedlbauer most fungi die at temperatures over 80°C, temperatures that do not occur in buildings. Fungi also die when the source of nutrients is removed or exhausted or in case excrements of the fungi contaminate the local environment too much. According to Beuchat [1987] the fungus' DNA collapses at relative humidities as low as 55%. Active fungi, however, are able to create their own microclimate for a limited amount of time which compensates for low RH values. After active fungi die, germination has to take place again for new spores to become active. Predicting death of active fungi might not be important for risk assessment purposes – germination and actual growth of fungi already give rise to serious concern – it is important in this study because the effect of temperatures and relative humidities over longer periods (years) is assessed. An RH of 55% or less during at least one month is estimated to cause active fungi to die.

In ASHRAE [2007] a fungal growth table is presented that shows RH values at which mould growth occurs for different materials, examined by Groom and Panisset in 1933. These materials are biologically degradable materials: parchment, cotton and goat skin; category I in Sedlbauer's model. The predicted RH for fungal growth by Groom and Panisset is a few percent lower than in Sedlbauer's model, but does not differ much from the current insight especially regarding the fact that measuring high RH values was not possible accurately at that time.

Mechanical degradation

Figure 3.3 shows an example of a stress-strain diagram. When applying stress to a sample of wood, the sample becomes longer. For small stresses, the stress and the strain (change in dimension expressed as fraction) show a linear behavior: wood reacts elastically when loaded in tension and returns to the initial dimension when stresses are released. At some point, an increase in stress causes more strain than expected from this linear connection: this point is called the 'yield point'; for wood in tangential direction this usually corresponds to a strain of 0.004. At stresses above the yield point, wood shows a permanent deformation (plastic deformation): when stresses are released the wood will not return to its original dimension. Stresses that cause the breaking of wood usually need to be 3 times higher than the stresses to cause plastic deformation.

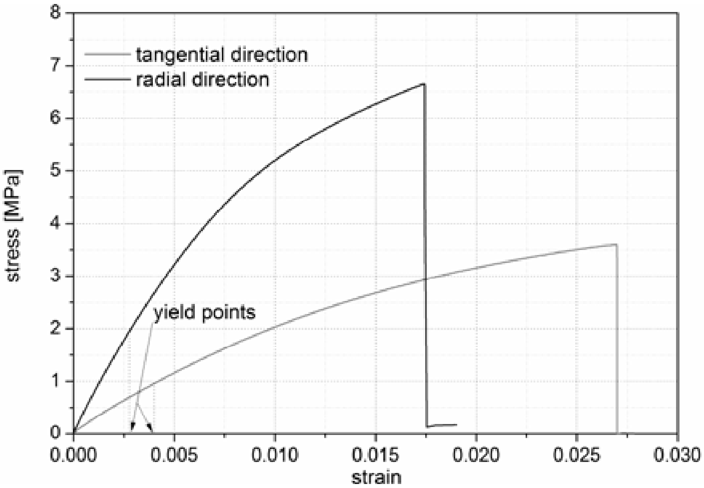


Figure 3.3: Yield point and failure stress for lime wood in tangential and radial direction [Kozlowski, 2011].

Externally applied forces lead to stresses in materials and therefore to changes in dimension. In materials that are not allowed to move freely, stresses also occur when the materials react to the indoor climate and want to swell or shrink. Stresses larger than the yield point of the material (but smaller than the fracture strength) lead to irreversible deformation. Both fracture strength and yield point are material properties and are determined under laboratory conditions: these values are known. In practice, both fracture and deformation need to be avoided in order to prevent damage and loss of value of an object.

It is important to note that strain is a better indicator than stress when assessing damage to objects. When a constant force is applied to a material, the initial dimensional change as indicated in figure 3.3 will increase slowly over time because of creep. When a constant strain is applied to a material, stresses will slowly decrease over time due to relaxation. Both creep and relaxation are complex material properties that are not discussed in this thesis. Moreover, creep and relaxation are not important when dimensional changes occur due to shorter fluctuations.

As stated above, damage is predominantly due to dimensional changes in materials that are restrained from movement. There are however two sources of restraint and related mechanical damage that need to be clarified. The first type of damage is caused by a slow RH change over time. The entire object responds to this slow change thus creating dimensional changes of the materials that can be hindered by the construction of the object. The second type of damage is caused by short changes in RH. Only a small part of the object – usually the surface – responds to this change, thus creating a difference in equilibrium moisture content between the bulk and the surface of the material. The bulk hinders the surface in movement.

Relative humidity plays a complicated role in the mechanical degradation process [Erhardt, 1994]. The main influence is dimensional change in materials caused by changes in equilibrium moisture content. Moreover some physical properties of materials change, e.g. hide glue softens and loses adhesive strength when being in equilibrium with RH values over 80%.

In stable humidity conditions only damage is encountered if object components are too soft and lack proper support or adhesion or are not strong enough to cope with being handled. But damage also occurs due to fluctuations in the indoor climate. Changes in RH do not lead to problems in materials that are free to expand or contract. Large changes can however lead to damage to objects that are made of combinations of materials. How large these changes need to be before actual damage occurs varies from object to object. Moreover, not all fluctuations cause the same amount and type of damage. Michalski [1993] states that fluctuations with a period under one hour do not affect most museum objects. Outer layers of untreated wood respond faster than the object as a whole, but furniture responds fairly uniform throughout its thickness due to typical coatings; the response time of the wood just under the coating does not differ much from the response time of the bulk. Fluctuations that cause the most strain in objects are longer than the object's response time: the time needed for the object to react to a change in RH. These fluctuations lead to deformation if the strain is larger than the strain at yield point.

For damage prediction, next to fracture strength and yield point also dimensional change for changing RH values is an important material property. Figure 3.4 shows an example of dimensional change for cotton wood (poplar); most hygroscopic materials behave similarly.

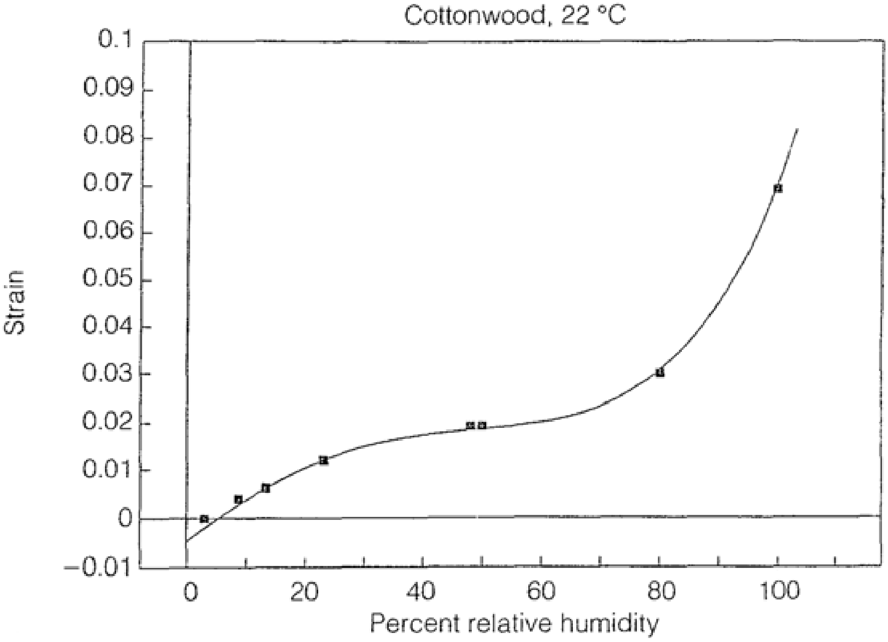


Figure 3.4: Dimensional change in cotton wood for adsorption and desorption [Mecklenburg et al. 1998].

In figure 3.4 strain – the dimensional change – of wood is plotted against relative humidity. For most materials the slope of the graph has its minimum around 50%RH; near 0% it is twice as steep and at high RH values even three times. This has two major implications: fluctuations in the middle region of RH cause less stress than the same fluctuations in a low or high RH range; also if a fluctuation is twice as large the strains caused by this fluctuation are more than twice as large.

Please note that figure 3.4 only considers wood in the tangential direction; this is the direction in which wood responds the most. In radial direction the response is about half the values presented here; in longitudinal direction responses are small. But the dependence on RH as described above is the same for all directions.

Apart from mechanical properties also some material properties change when the RH – and therefore the material's moisture content – changes. For gesso the relaxation time changes from days to months at low RH; low RH values therefore lead to more cracking. Fluctuation damage also depends greatly on geometry of the objects [Michalski, 1993].

To prevent damage it is important to avoid strains that exceed the yield point, because these strains lead to plastic – and therefore irreversible – deformation and/or cracking. Prediction of strains in materials is the key factor for assessing mechanical degradation. The magnitude of these strains depends, according to Erhardt [1994] on:

- dimensional response of a material to RH (moisture coefficient of expansion);
- change in stiffness of the material (modulus);
- degree of restraint of the material (depending on the construction of the object) and
- magnitude and rate of change in relative humidity (penetration depth and stress gradient).

Not all materials are equally vulnerable to cracking. The cracking potential is defined by:

- material strength;
- ability to deform;
- presence of defects in the material and
- fracture sensitivity.

An exact knowledge of specific objects is needed in order to predict the mechanical degradation. There is a large variety in materials and constructions found in museum collections. A very important type of object are panel paintings; paintings made on one or several wooden panels. The response of individual layers in a wooden panel painting has been studied by Mecklenburg [1994]. The objects construction causes restraints; these restraints prevent joined wood from swelling and shrinking in response to RH variations. Wood can also act as its own restraint in case of uneven moisture distribution. Moreover, also paint and other design layers parallel to the grain of the wood may restrain the wood itself; also the response of the design layer itself causes restraints perpendicular to the grain of the wood. Response rates of various materials to changes in RH become important here.

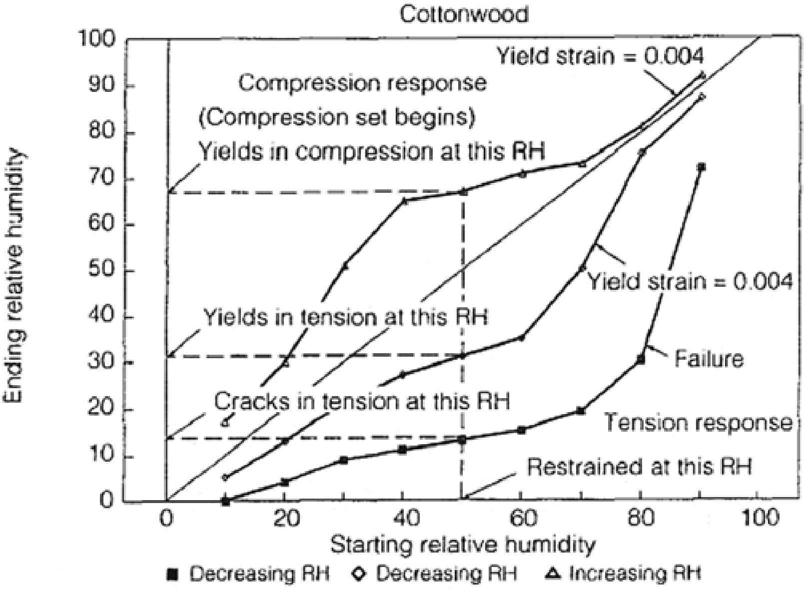


Figure 3.5: The response of cottonwood to changes in RH – fully restrained in tangential direction [Mecklenburg et al, 1998].

Graph 3.5 is based on response to a step change in RH of cottonwood (or poplar). For each combination of starting and ending RH the resulting damage can be assessed. Changes in the elastic region (in between curves for yield strain = 0.004) do not cause degradation to paintings. Changes in the failure region immediately lead to cracks in materials. In between these regions, plastic deformation occurs which might lead to failure after several RH change cycles. The graph assumes full response to step changes in RH.

Detection of damage could only be performed by viewing whether an object is intact or cracked. Recently a new approach in assessing damage on a smaller scale was introduced. Kozłowski [2007] developed an acoustic measurement setup in order to determine whether micro-cracks occur in wood. These cracks show a specific acoustic characteristic, which opens the possibility to predict damage caused by fluctuating temperature and/or relative humidity.

Jakieła et al [2007] modeled a lime wooden cylinder with a diameter of 13 cm that was in equilibrium with different RH levels. Step and diurnal changes were applied. Dimensional changes and therefore stresses in the wood were calculated; these stresses were related to damage. The results of this study are displayed in figure 3.6.

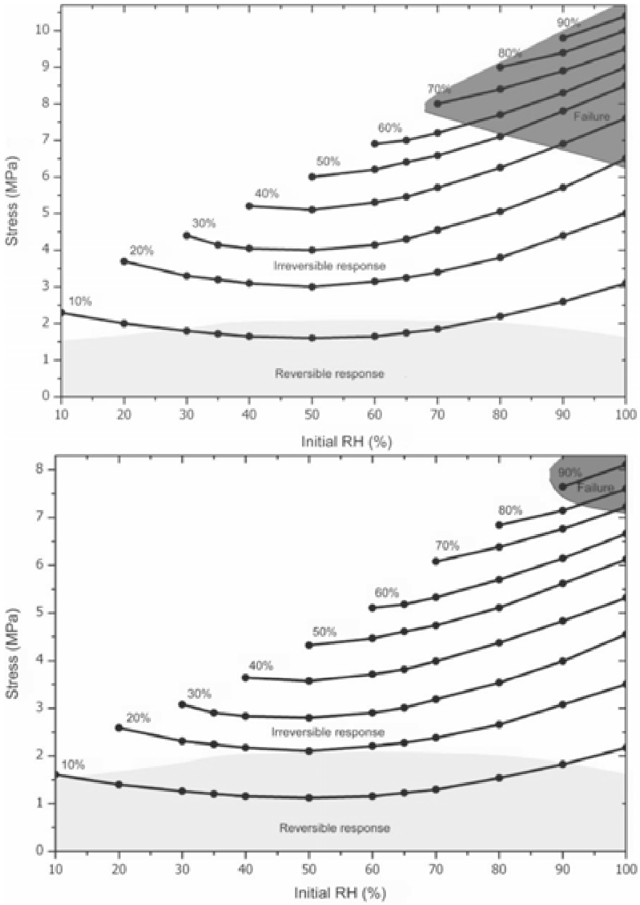


Figure 3.6: Stress induced by step RH variations (top) and 24h sloped (bottom) between 10% and 90%, plotted as a function of the initial RH level from which the variation starts [Jakieła et al., 2007].

The top figure shows the response of a wooden cylinder to a sudden drop in RH. The bottom figure is the result of a gradual decrease in RH during one day; initial and final RH values are similar to the top figure. Stresses caused by a sudden step (top) or gradual step (bottom) are given; the area in which stresses lead to cracking is colored and marked 'failure'. The area of safe reversible response has a lighter color. As can be seen from both graphs an average value of around 50% is beneficial for wooden sculptures; stresses can be higher before plastic deformation occurs. The difference in reversible response shows that fast changes can cause damage to massive wooden objects while slower gradual changes are less harmful.

Figure 3.7 displays the same data in another format. The initial value in figure 3.6 corresponds to the starting RH as displayed in figure 3.7. For each 10% step in initial RH the RH change corresponding to reversible response is determined and subtracted from the initial RH; this is the ending RH in 3.7. The top graph of 3.6 corresponds to the solid lines; the bottom graph determines the dotted lines. Due to the symmetry of these graphs, reversible response lines are mirrored using a 45 degree line (light grey).

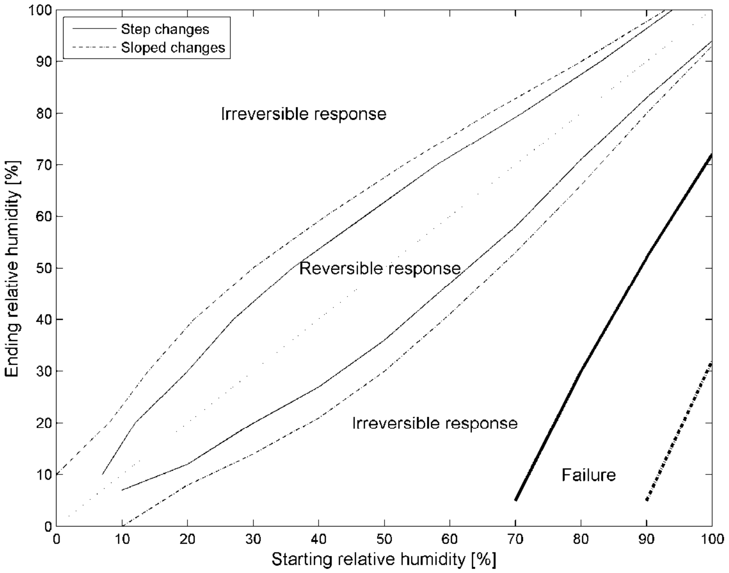


Figure 3.7: The response of lime wood to changes in RH; Jakiela's graphs in another format. Step changes are displayed as solid lines, while sloped changes are dotted.

When comparing figure 3.5 and 3.7 the reversible response region has a similar shape: narrow at low and high relative humidity and wide at RH values in the middle region. The graphs do not match entirely. This is mainly due to the differences in the moisture absorption and desorption curves Mecklenburg and Kozłowski used in their research.

It should be noted that in both graphs relaxation of stresses over time is not accounted for; only short changes in RH are considered. Relaxation plays an important role in wooden artifacts when considering seasonal changes.

Stresses induced due to RH changes are not limited to wood only. A panel painting consists of a wooden panel, a gesso layer to smoothen the wood and a pictorial layer. The pictorial layer on the wood substrate may experience stresses due to the mismatch in the dimensional response of gesso and wood in unrestrained panel paintings, especially in the most responsive tangential direction of the wood: upon desiccation, the shrinkage of wood overrides that of the gesso which experiences compression, whereas upon wood swelling, the gesso layer experiences tension [Mecklenburg et al., 1998]. If the uncontrolled changes in the moisture-related strain go beyond a critical level, the gesso can crack or delaminate. Furthermore, the critical strains causing damage were determined experimentally as a function of the number of strain cycles and thus the vulnerability of the design layer to fatigue fracture – a consequence of the cumulative strain effects – was assessed. Figure 3.8 shows which strain leads to cracks in the gesso layer applied to a lime wooden specimen. Strains less than 0.15% do not lead to damage, not even in the long run. A strain of 0.45% leads to cracking of the gesso after just one cycle. Intermediate strains need a certain number of cycles before the first crack occurs; 0.4% corresponds to 200 cycles. This means an expected time for a first crack to appear in the object of 200 years if this cycle has a period of one year; in case of a weekly cycle this time is only 4 years.

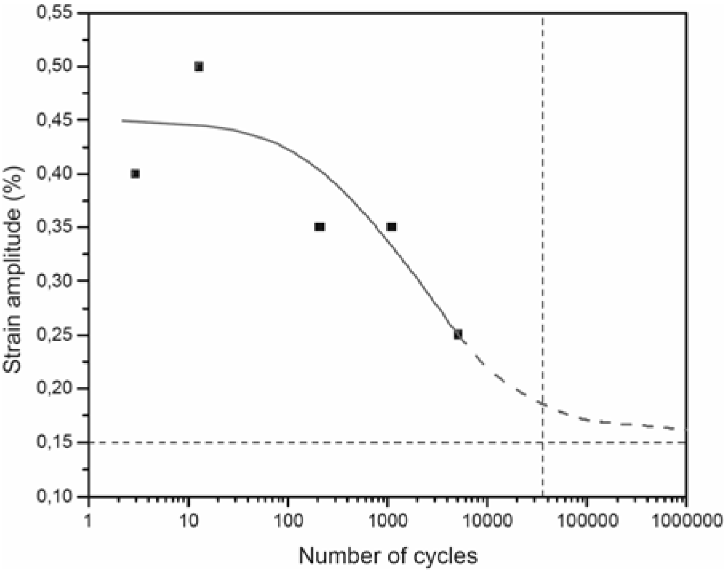


Figure 3.8: Number of cycles before strain leads to cracking; the horizontal dotted line represents a safe limit for which strain will not lead to damage. The vertical dotted line represents 36.500 cycles (daily changes lasting for a century) [Bratasz et al, 2010].

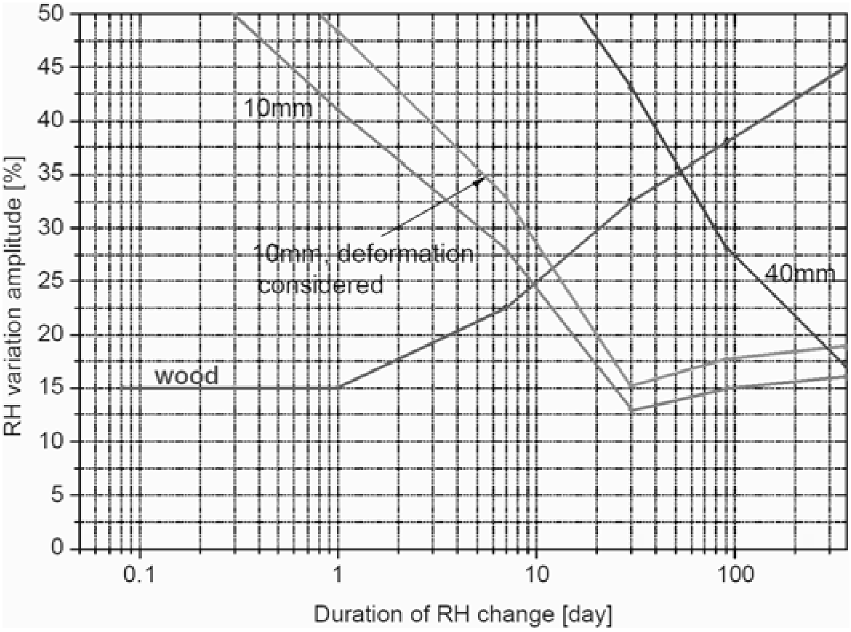


Figure 3.9: RH variations which do not cause damage to gesso on lime wooden panels of 10 and 40 mm thick and massive wood during a period of 100 years [Bratasz et al, 2010].

Also the response time of materials needs to be taken into account. Very fast RH cycles are not noticed by the bulk of the material, so there can be no full response to these cycles. Figure 3.9 shows for 2 lime wooden panels – 10 and 40 mm thick – which amplitude leads to damage to the gesso layer when taking into account the duration of RH change. A period of 100 years is taken into account, so duration of RH change of 1 day leads to 36500 cycles in 100 years; according to figure 3.8 the corresponding strain is 0.19%.

The lines in figure 3.9 have a minimum because when the duration of the cycle goes beyond the response time of the panel, its allowable amplitude increases as fewer cycles would occur in the period of 100 years considered.

Also a line for damage to wood is plotted. Variations in RH lead to gradients in wood: the outer layer responds faster than the material below: stresses occur. Slower variations cause less damage because gradients are smaller and relaxation of stresses takes place. This is represented by the dotted line.

It is important to note that results displayed in figure 3.9 are only valid for changes in RH around 50% RH and for sine signals of constant amplitude and period.

Chemical degradation

Chemical degradation is the only remaining concern when mechanical damage is reduced and fungal growth avoided; it is however often neglected. Chemical processes depend on or are accelerated by water [Erhardt et al, 1994]. The amount of water in hygroscopic materials increases as the RH increases; moreover each extra molecular layer of water is less tightly held by the material and is more available for reactions, thus increasing reaction speed. This reaction speed decreases at low humidity. Also lowering temperature is used to slow down chemical processes; this is used in many long-term storage facilities [Erhardt et al, 1994].

Generally a lower RH means lower moisture content and therefore slower deterioration. When only chemical degradation is taken into account, RH values down to 2% are beneficial for the lifetime of an object [Erhardt et al, 1994]. However this might be in conflict with the mechanical degradation if handling of objects or a sudden change in RH takes place!

The methods used to determine the speed of deterioration are under discussion. Aging is a very slow process; e.g. at 20°C and 50% it takes about 30 to 100 years before newspaper fragments become unusable [Ankersmit, 2009]. To be able to do measurements on deterioration rates within a reasonable time span, the aging process is sped up under laboratory conditions. This speeding up might change material properties thus influencing deterioration rate. To solve this issue, Zou [1996a, 1996b] analyzed cellulose degradation. He concluded that cellulose shows a behavior proportional to the Arrhenius equation:

$$k = A \cdot e^{\frac{-E_a}{R \cdot T}} \tag{3.1}$$

In which: k Reaction rate constant [1/s]

A Frequency rate constant [1/s]

E_a Activation energy [J/mol]

R	Gas constant [8.314 J/Kmol]
T	Temperature [K]

This equation is used to calculate degradation speed; tests in which high temperatures are used to obtain deterioration speeds at room temperatures are allowed when using cellulose.

When comparing measurements on degradation at different temperatures and relative humidities, Michalski [2003] concludes that around 20°C for most objects the expected lifetime doubles for a 5K drop in temperature. The Arrhenius equation is however not correct for low RH, Michalski [2003] corrects this by applying a power law in which n equals 1.3. The following equation is constructed for the Lifetime Multiplier, which is defined as the number of time spans an object remains usable when compared to a condition of 20°C and 50%RH:

$$LM_x = \left(\frac{50\%}{RH_x}\right)^{1.3} \cdot e^{\frac{E_a}{R}\cdot\left(\frac{1}{T_x}-\frac{1}{293}\right)} \tag{3.2}$$

In which:

LM_x	Lifetime multiplier at point x [-]
E_a	Activation energy [J/mol]
R	Gas constant [8.314 J/Kmol]
T_x	Temperature at point x [K]
RH_x	Relative Humidity at point x [%]
x	Data point in data series [-]

The activation energy, the energy that must be overcome for a reaction to occur, depends on the type of materials the object consists of. According to Michalski [2003], it ranges between 70 and 100 kJ/mol for most materials; 70 for yellowing of varnish and 100 for degradation of cellulose. When looking at formula 3.2 it can be seen that this activation energy influences the thermal part of the equation, not the hygrical part.

Figure 3.10 shows a psychrometric chart that contains lines of equal lifetime multipliers. Solid lines are used for activation energy of 70 kJ/mol and dashed lines for 100 kJ/mol. At 20°C the expected lifetime for both energies is equal (by definition); the solid lines show a steeper slope. This means that a temperature drop is more beneficial to prevent degradation for materials with high activation energies.

If a 5K drop (from 20 to 15 °C; the RH remains 50%) is considered; when Ea equals 70 kJ/mol the expected lifetime multiplier is 1.65; for an Ea of 100 kJ/mol it equals 2.04. This also supports the conclusion that the temperature level has a smaller effect on degradation for materials that have lower activation energies.

Lifetime Multipliers are determined out of the climate close to an object. This is not entirely correct. According to Strang et al [2009], in paper fibers the water concentration in the cell wall has a direct effect on the degradation rate of paper. The moisture retention curve – which links water content to relative humidity of the air close to the cells – needs to be taken into account when considering reaction speed. Current measurements, however, are not satisfactory for determining this new relation.

The lifetime multiplier is especially important for paper objects. Other objects in most cases have a varnish or paint layer that is replaced every few decades. Although the varnish deteriorates according to equation 3.2, it is removed and reapplied after which the deterioration starts again. For these objects varnish is a protective layer and not part of the object.

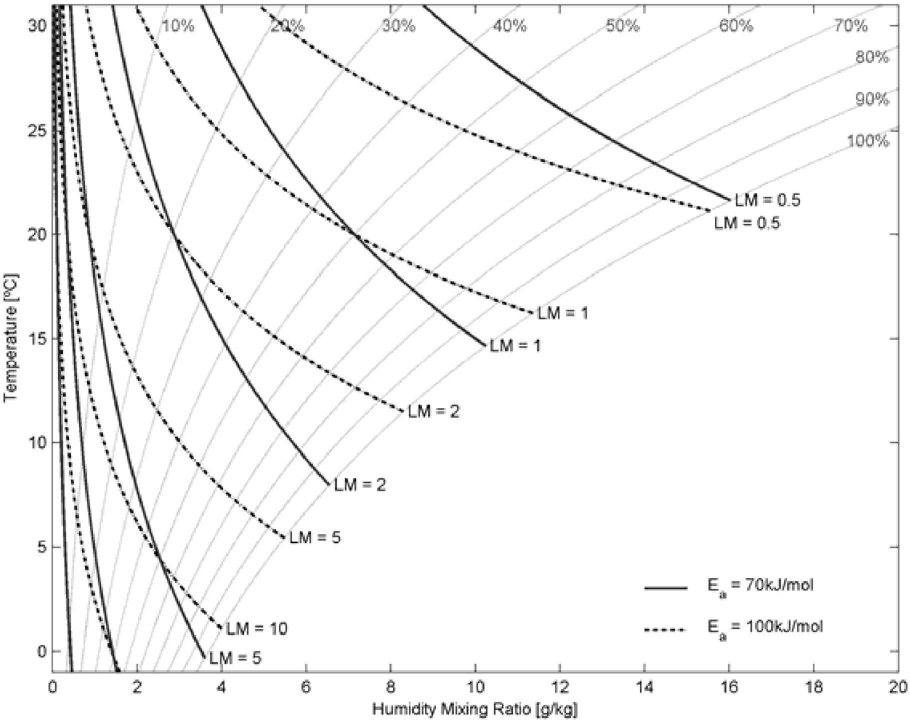


Figure 3.10: Lifetime Multiplier curves in a psychrometric chart (see Chapter 2) indicating combinations of T and RH for various LM values, for activation energies of 70 and 100 kJ/mol.

3.2. CHARACTERIZING INDOOR CLIMATES

In order to characterize indoor climates some statistical operations can be used; the indoor climate is described in terms of averages and fluctuations. This is explained in paragraph 3.2.1. The general climate risk assessment method describes how the indoor climate fits into the ASHRAE climate guidelines; paragraph 3.2.2 provides detailed information on how to do this.

3.2.1. Statistical operations

Each indoor climate can be characterized by a set of unique parameters produced by statistical operations: averages, seasonal changes and shorter fluctuations in temperature and RH. The first step in the calculation process consists of filtering out measurement errors: exotic values might influence the calculated output.

This is done by taking 0.1 percentile up to 99.9 percentile as the valid data range; this means that of every 1,000 data points the lowest value and the highest value are left out.

The first statistical property of the measured climate is the yearly average value. This value is determined by taking one year of data and using formula 3.3. Formula 3.3 is only valid when the time interval between all data points is equal. In figure 3.11 an example of measured temperatures is displayed; also the calculated yearly average is shown.

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \qquad (3.3)$$

In which:	$\overline{X}$	Annual mean in T [°C] or RH [%]
	X	T [°C] or RH [%]
	n	Number of data points [-]
	i	Data point in the data range [-]

It should be noted that for the average relative humidity an error is introduced by using formula 3.3. RH is not a primary quantity: it is dependent on temperature. In order to calculate the average RH, it would be more appropriate to calculate average humidity mixing ratio and average temperature and determine the corresponding RH. The error introduced when calculating average RH directly is very small: usually less than 1%RH in unheated rooms and nearly 0%RH in rooms in which temperature is kept constant. Therefore it is chosen to use formula 3.3 also for RH.

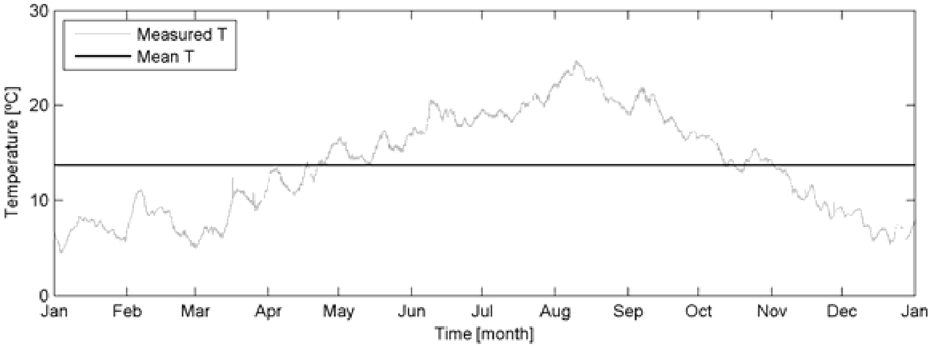


Figure 3.11: Example of measured temperature and average temperature.

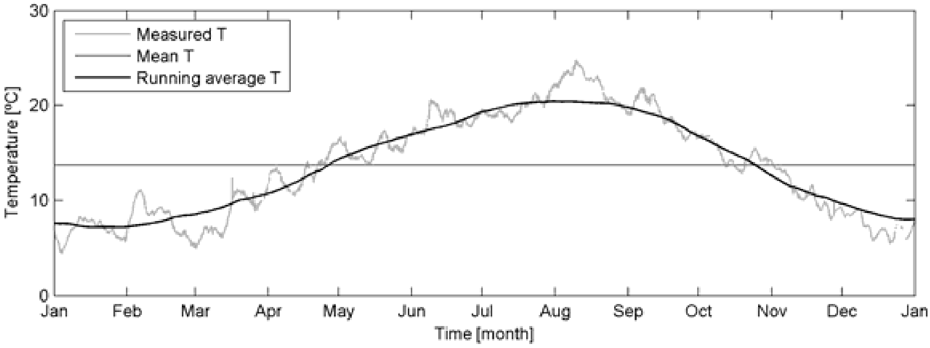


Figure 3.12: Example of measured temperature, average temperature and seasonal running average temperature.

To estimate the seasonal change in the climate, a running average is calculated that uses a period of one season (three months or 91 days). This period is centered, which means for each value looking back one month and a half and looking forward one month and a half. This is done to make sure the calculated running average does not shift in time compared to the original curve. Formula 3.4 is used to calculate this running average; figure 3.12 displays the result. Because of the averaging a longer period of data is needed: instead of 1 year also 1.5 months before and after the period are needed in order to calculate the seasonal running average. This is done by mirroring the original data.

It is important to note that this average is not the average experienced by the collection. Not only is the response time not equal to three months for most objects, but objects cannot have experienced the future climate and are therefore only in equilibrium with the past climate.

$$X_{\text{running},\,i} = \frac{1}{n} \sum_{a=i-0.5\cdot n}^{i+0.5\cdot n} X_a \qquad (3.4)$$

In which:	
X_{running}	Seasonal running average in T [°C] or RH [%]
X	T [°C] or RH [%]
n	Number of data points in one season [-]
i	Current data point in the data range [-]
a	Point in seasonal period [-]

To determine the difference between the maximum value in the running average and the annual mean, formula 3.5 is used:

$$X_{\text{rise}} = \max(X_{\text{running}}) - \overline{X} \qquad (3.5)$$

In which:	
X_{rise}	Seasonal rise in T [°C] or RH [%]
X_{running}	Seasonal running average in T [°C] or RH [%]
$\overline{X}$	Annual mean in T [°C] or RH [%]

Also the difference between the annual mean and the minimum value is determined; formula 3.6 is used. Figure 3.13 displays an example of calculated seasonal adjustments.

$$X_{\text{drop}} = \overline{X} - \min(X_{\text{running}}) \qquad (3.6)$$

In which:	
X_{drop}	Seasonal drop in T [°C] or RH [%]
$\overline{X}$	Annual mean T [°C] or RH [%]
X_{running}	Seasonal running average in T [°C] or RH [%]

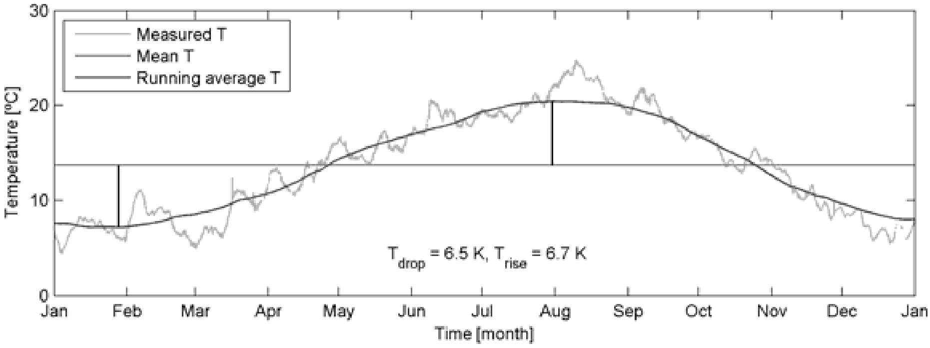


Figure 3.13: Example of measured temperature, average temperature, running average temperature and temperature rise and drop.

As mentioned before, short fluctuations are important to estimate mechanical damage to objects. For this reason the weekly, daily and hourly changes in temperature and relative humidity are calculated. The average fluctuation and the standard deviation are determined.
The differences are described by the following formula:

$$\Delta X_{\text{periodically}, i} = \max(X_{i-n}, X_{i-n+1}, ..., X_i) - \min(X_{i-n}, X_{i-n+1}, ..., X_i) \tag{3.7}$$

In which:		
	$\Delta X_{\text{periodically}}$	Change in T [ºC] or RH [%] over a certain period
	X	T [ºC] or RH [%]
	n	Number of data points in one period [-]
	i	Data point in the data range [-]

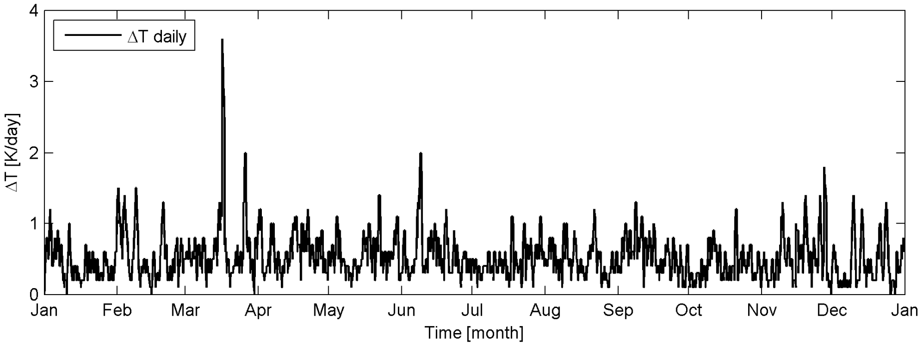


Figure 3.14: Example of daily temperature differences.

When the periodic changes in T and RH are calculated, formula 3.3 is used to calculate the mean value. The standard deviation is determined by the following formula:

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i - \bar{X})^2} \tag{3.8}$$

In which:

σ	Standard deviation
$\overline{X}$	Annual mean T [°C] or RH [%]
X	T [°C] or RH [%]
n	Number of data points [-]
i	Data point in the data range [-]

Results for this method for one room and one museum are given in paragraph 3.3. In Chapter 4 this method is executed on all measurement data.

3.2.2. General climate risk assessment

ASHRAE climate classes are normally used as design parameters; the values given in table 3.1 are used as set points of a climate system. In this case the opposite operation is specified: set point values and bandwidths are used to assess measured climate data.

The average temperature and relative humidity are determined using formula 3.3. These averages are used as the 'historic annual average' mentioned in the second column of table 3.1. Also the seasonal running average is determined using formula 3.4 for both temperature and relative humidity.

According to table 3.1 the temperature set point should be between 15 and 25°C, mostly for reasons of human comfort. For collection purposes temperature is allowed to be lower than 15°C. In fact, a lower temperature can be beneficial to the collection since chemical degradation decreases at lower temperatures. Moreover, yearly average temperature in unheated historic buildings in the Netherlands is lower than 15°C, disqualifying the use of ASHRAE guidelines. Therefore the decision is made not to include these temperature restrictions.

Class C and D state an absolute minimum and maximum for the relative humidity of 25% and 75% (D only the maximum). These restrictions are not specified in classes AA, As and A. If one starts at an annual historic value of around 50% these values are not reached, but when the yearly average value differs substantially from 50% this might be the case. The decision is made not to include 25% and 75% limits for the stricter classes; therefore the possibility exists that very moist or very dry conditions show a better similarity for the better classes than for class C and/or D.

Each climate class is approached individually. The calculated annual average and the seasonally allowed changes are used to determine the minimum and maximum value for the allowed seasonal shift. If the calculated seasonal running average is below the minimum or above the maximum allowed value, the average value is replaced by this limiting value. The allowed short fluctuations are used to determine the bandwidth: the running average curve is lifted by the allowed short fluctuation to provide for the maximum curve and lowered for the minimum curve.

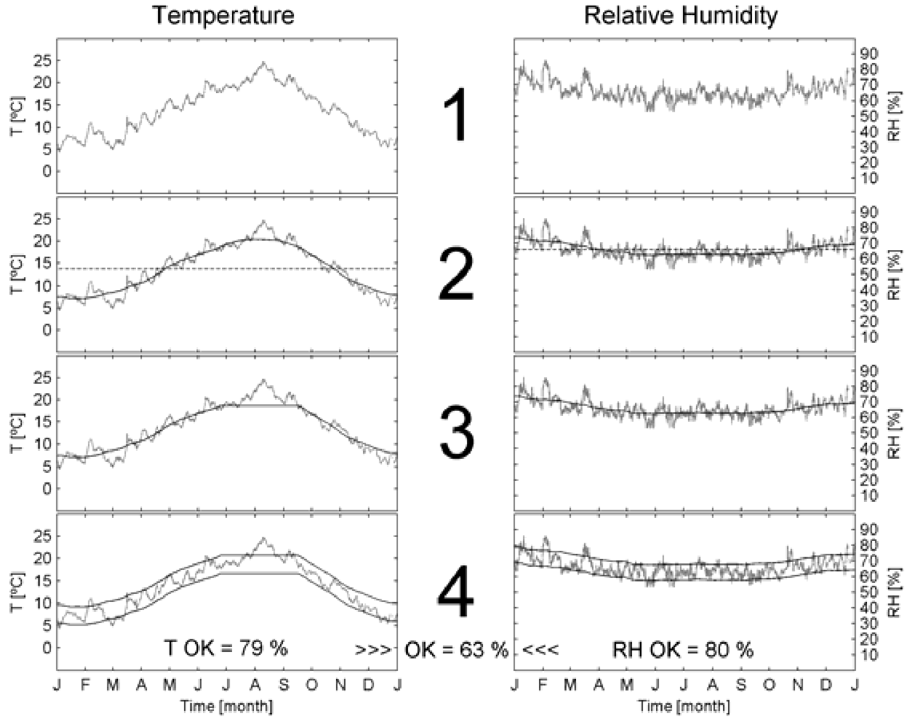


Figure 3.15: Example of comparing measurement data to ASHRAE class As. (1) shows temperature and humidity, (2) shows annual mean and seasonal running average, (3) displays seasonal running average limited conform ASHRAE As and (4) shows total bandwidth and percentage of data in this bandwidth.

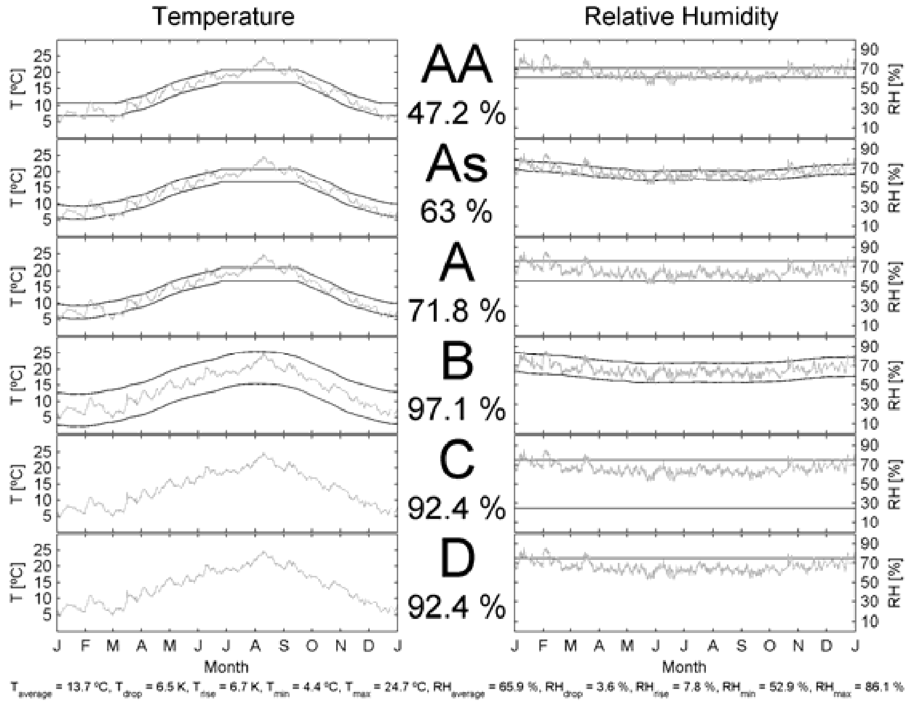


Figure 3.16: Comparison of measured data to the ASHRAE climate classes AA up to D.

Figure 3.15 shows an example of comparing a data set to ASHRAE climate class As. The top graphs (1) show temperature and humidity over time. Graphs (2) show the calculated annual mean and the seasonal running average. Graphs (3) display the limiting factors for class As: the seasonal temperature increase should not be more than 5K. In July, August and September the seasonal running average minus the annual mean is larger than 5K: these temperature values are reduced to the annual mean plus 5K. The bottom graphs (4) show the minimum and maximum curves. The graph also displays the percentage of the total period each individual parameter (temperature or RH) is OK. In between the graphs the percentage that both parameters are OK simultaneously is displayed.

Although the average T and RH are the same for all climate classes, the differences in allowed seasonal change and bandwidth make sure that for each climate class a different result is obtained. An example of a comparison is shown in figure 3.16. The original data is presented in grey. The black lines are the minimum and maximum values allowed for each climate class. In the center for each climate class a percentage is given: the amount of time the properties of each class are met simultaneously.

3.3. EXAMPLES

In paragraph 3.3.1 results for one room in a museum are generated and discussed. In 3.3.2 every room in this museum is assessed and compared. Results for all museums are discussed in chapter 4.

3.3.1. One room

Results for Museum 5 Room 1 are displayed. Figure 3.17 and 3.18 give a graphical representation of the statistical parameters and the general climate risk assessment method.

Figure 3.17 gives a statistical representation of the indoor climate in Museum 5 Room 1. The top graph displays temperatures. The measured climate is plotted in light grey, while the annual mean is dark grey and the seasonal running average is black. Vertical black lines mark minimum and maximum seasonal averages. The second graph displays relative humidity. Also here annual mean RH (dark grey), seasonal running average (black), original measured data (light grey) and minimum and maximum seasonal RH (vertical, black) are given. The bottom left graph shows hourly (grey), daily (black) and weekly (light grey) temperature changes, while the bottom right graph shows the same for relative humidity. Below the bottom graphs some numbers are displayed. These correspond to average and seasonal change values of T and RH and also to average changes and standard deviation in these changes.

Room 1 is quite warm and dry; yearly averages of 23.0 °C and 38.6% were measured. Seasonal changes are small for temperature (-2.1K / +1.2K) but larger for relative humidity (-13% / +15%). Short fluctuations in temperature average at 0.3K per hour (standard deviation of 0.4K), 2.9K per day (standard deviation of 1.1K) and 5.0K per week (standard deviation of 1.3K). For relative humidity, short fluctuations have a mean value of 1.4% per hour (standard deviation of 1.9%), 11% per day (standard deviation of 4.4%) and 23% per week (standard deviation of 5.5%).

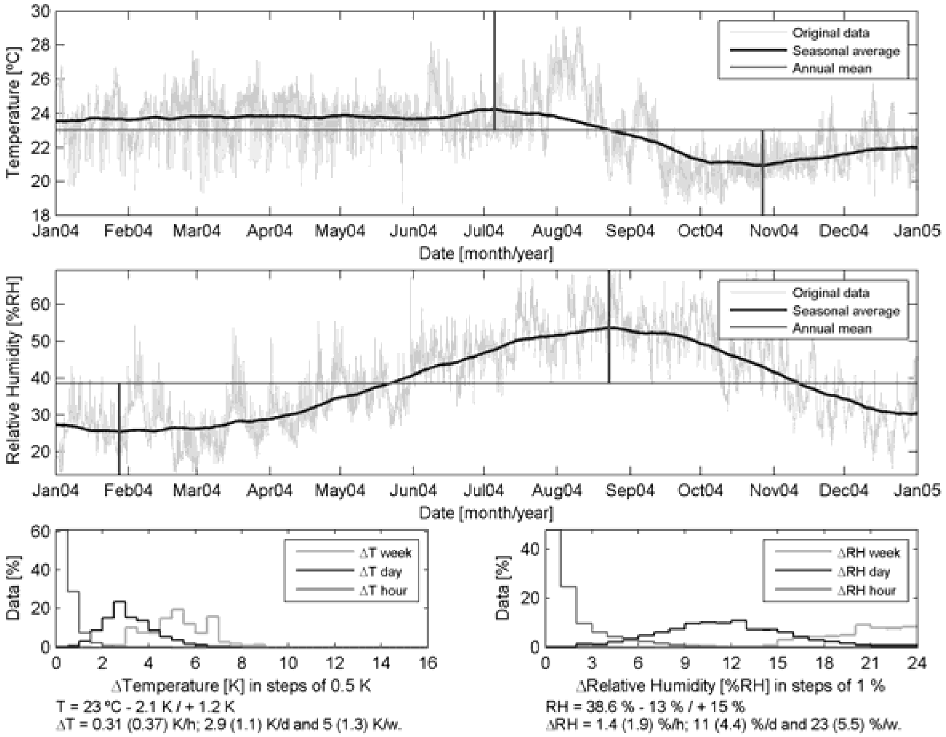


Figure 3.17: Statistical operations for Museum 5 Room 1.

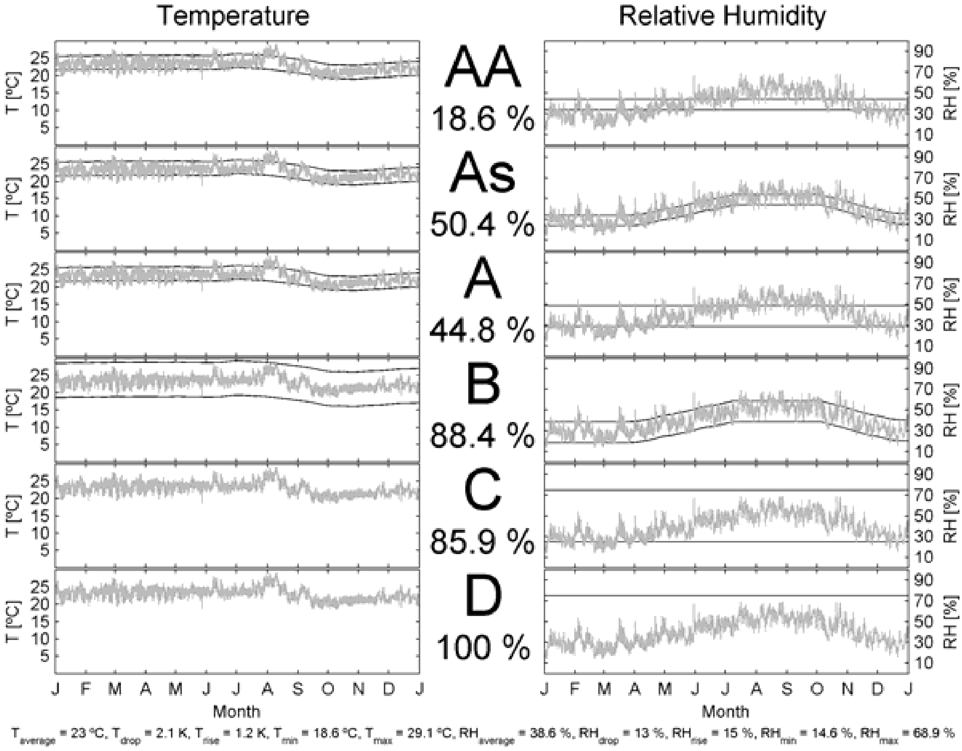


Figure 3.18: General climate risk assessment method for Museum 5 Room 1.

Figure 3.18 shows results for the general climate risk assessment method. Because of the large seasonal change in relative humidity class AA does not have a high score: 18.6%. This means that during 18.6% of the measured period the indoor climate fits the criteria for this class. Since seasonal changes are large but short fluctuations are smaller, As shows a higher percentage than A, 50.4 and 44.8% respectively. Class B, in which both seasonal and short fluctuations are allowed to vary more, is met 88.4% of time. Class C and D obtain a percentage of 85.9 and 100%, meaning that the RH always remains under 75% but is lower than 25% in 14.1% of the measured period. The risks to the objects exposed to this climate are best described by the risks for class D, because class D is met 100% of the measured period.

3.3.2. A museum

When a whole museum is under research, results obtained from statistics or the general climate risk assessment method need to be combined in tabular form in order to asses the climate in the museum. Tables 3.2 and 3.3 displays results for Museum 5.

Table 3.2 shows that part of Museum 5 is heated (room 1, 5 and 7). The annual mean temperature is higher and also a lower average RH is encountered. The non-heated rooms show a winter drop in temperature of about 4 to 7K, while heated rooms show a 2 to 3K drop. In RH the effect is opposite: heated rooms show a large seasonal change in RH while non-heated rooms are more constant throughout the year. Daily and weekly changes in temperature and relative humidity are largest in room 8, which is located in the attic of Museum 5.

Table 3.2: Statistical operations for Museum 5: calculated temperatures and relative humidities.

Method 1: Statistical	Temperature						Relative Humidity					
Museum 5	Mean	Drop	Rise	Δhour	Δday	Δweek	Mean	Drop	Rise	Δhour	Δday	Δweek
Room 1	23.0	2.1	1.2	0.3	2.9	5.0	38.6	13.1	15.1	1.4	11	23
Room 2	15.3	4.2	4.7	0.08	0.8	2.2	62.3	3.1	4.5	0.6	5.4	14
Room 3	13.7	6.5	6.8	0.03	0.53	2.1	65.9	3.6	7.8	0.4	4.0	11
Room 4	13.1	5.3	4.9	0.2	1.8	3.8	72.4	3.8	4.7	1.1	9.8	23
Room 5	21.8	3.2	1.7	0.1	1.4	3.5	41.6	9.4	13	0.6	7.0	17
Room 6	14.9	5.9	6.2	0.2	1.5	3.2	63.5	2.6	5.2	0.5	4.7	13
Room 7	17.9	2.0	2.1	0.2	1.6	2.8	56.2	16.4	12.4	1.0	9.5	23
Room 8	14.0	7.5	7.7	0.3	3.7	7.7	67.7	10.1	13.8	1.1	12	25

Table 3.3: General climate assessment method for Museum 5: percentage of data within each ASHRAE class.

Method 2: ASHRAE	ASHRAE climate classes					
Museum 5	AA	As	A	B	C	D
Room 1	18.6	50.4	44.8	88.4	85.9	100
Room 2	68.4	78.0	92.8	98.5	99.8	99.8
Room 3	47.2	63.0	71.8	97.1	92.4	92.4
Room 4	46.0	49.8	77.4	88.1	60.0	60.0
Room 5	26.8	54.5	53.9	94.1	98.4	100

Room 6	59.6	67.7	81.2	97.6	98.5	98.5
Room 7	29.4	51.5	54.4	85.4	97.3	97.3
Room 8	15.7	31.5	32.1	84.2	70.6	70.6

Table 3.3 shows the ASHRAE percentages for each room and each climate class. Room 2 has the highest score for all classes except D. The worst room is room 8: the attic. Room 4 only scores 60% for class C and D because of the humid climate.

The results mentioned above are compared to a recent report on the condition of objects in Museum 5. According to this report some traces of fungal growth were encountered in Room 6; it is not known whether the fungi were active or had died. Paper objects in Room 6 showed minor degradation. An untreated, massive wooden object – kept in Room 4 for centuries – does not show any deterioration. Mould growth was found in Room 3 on wooden wainscoting. These results do not match results for the general climate risk assessment method exactly, which is mainly due to relocation of some objects. Fungal growth might have developed while the object was elsewhere in the building. Maybe the fungi were not active anymore: fungal growth stops when the climate conditions are better for a longer period.

3.4. CONCLUSIONS

Measurements on temperature and relative humidity are useful for assessment of indoor climates. Predicting preservation is an important aspect in preventing damage to objects. Both the statistical operations and the general climate risk assessment method presented in this chapter can be used to perform this assessment in a clear and structured manner. Although both have a different approach, they are usable in predicting risks and damage.

The statistical operations are very useful to obtain detailed information about the indoor climate. A time series of data is translated into a few parameters that make the comparison of different climates very easy. However, it expects a lot of knowledge from the user: the user has to interpret the results and find out whether a parameter is allowed for the preservation of an object.

The general climate risk assessment method translates a time series of data into a single percentage for each ASHRAE climate class. This makes it easy to compare both classes and measurement positions. Less knowledge of the user is required, because common risks to objects are already incorporated into the climate classes. The main problem with the ASHRAE climate classes is that when a climate class is met during a certain percentage of time, damage to objects usually occurs in the period the indoor climate is not within the climate class. This means that the risks, as proposed in the ASHRAE table, are only valid when the class is met 100% of time. In other words, the outliers determine whether damage occurs or does not occur.

Both methods, however, lack the response of objects to the indoor climate. For example, a wooden object without varnish tends to follow changes in room RH more closely than the same object with varnish. Also both methods tend to underestimate the influence of sudden changes in indoor climate.

4

General risk analysis

In chapter 3, statistical operations and a general climate risk assessment method have been presented. In this chapter, both are applied to the permanent measurement results (as described in chapter 2). The main purpose of this chapter is to identify differences in climate between museums, between levels of control, between qualities of envelope etc. By thoroughly going through the measurement data for all these types, preservation quality in an arbitrary building may be estimated without actual measurement. Moreover, it is helpful in understanding climate related preservation problems.

The first part of this chapter focuses on all measurement results: statistics and general risks are determined. The second part of this chapter focuses on specific problems that arose in some of the museums in this research. The third part states the main conclusions and discussions.

4.1. DATA ANALYSIS OF 20 DUTCH MUSEUMS

In this part of chapter 4, measurement data are used in exhibition rooms, storage areas and display cases. These 241 locations in 20 museums represent most of the conditions Dutch collections are exposed to. Each paragraph focuses on another aspect of the measured data, or sorts the data by type. In most cases all data is used, unless mentioned otherwise. In each graph the number of museums is displayed as m, the number of measurement locations – rooms in museums – as r.
In appendix B tables are presented that show all results for the average indoor climate conditions on 241 locations. In appendix C also results for surface conditions are displayed.

4.1.1. Statistical properties of measured indoor climates

Results for the statistical operations (see Chapter 3.2.1) are displayed in figure 4.1 to 4.6. These figures display the distribution determined by dividing the x-axis into portions and counting the number of measurement data in each portion. The total number of rooms is displayed in the legend using r, m stands for the total amount of museums. Figure 4.1 displays distribution of annual mean temperatures for exhibition rooms, display cases, storage areas and surfaces. The spread in temperatures is high in exhibition rooms: yearly average temperatures between 12 and 24°C occur. For storage areas and display cases temperatures are more tempered due to the lack of disturbances. In general display cases are warmer than storage areas. It is important to note that display case temperature closely resembles room temperature around the display case; the material of the display case is opaque for certain wavelengths, generating small amounts of heat. Moreover, display cases are not frequently used in unheated buildings as no display cases show lower yearly average temperatures than 17°C.

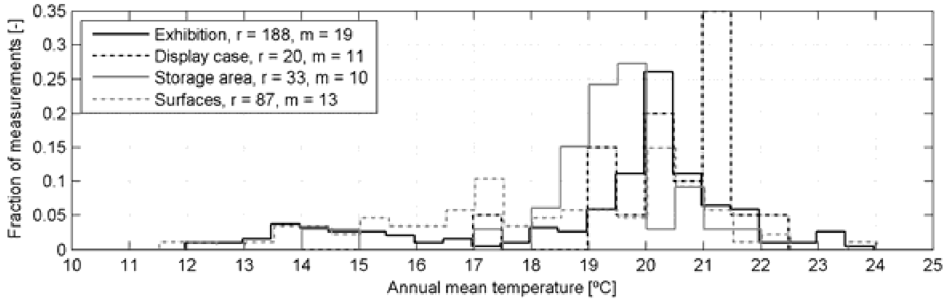


Figure 4.1: Annual mean temperature.

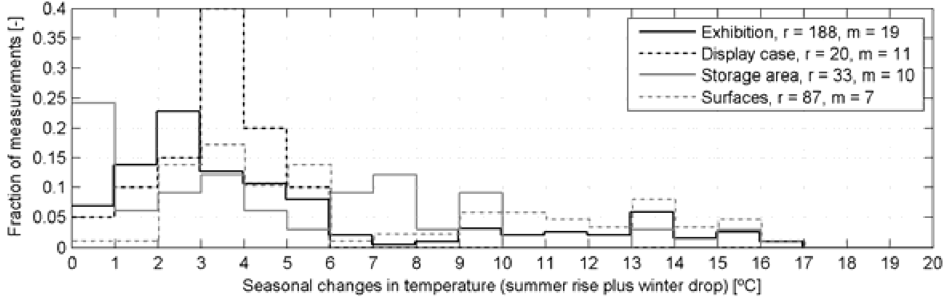


Figure 4.2: Seasonal adjustments in temperature.

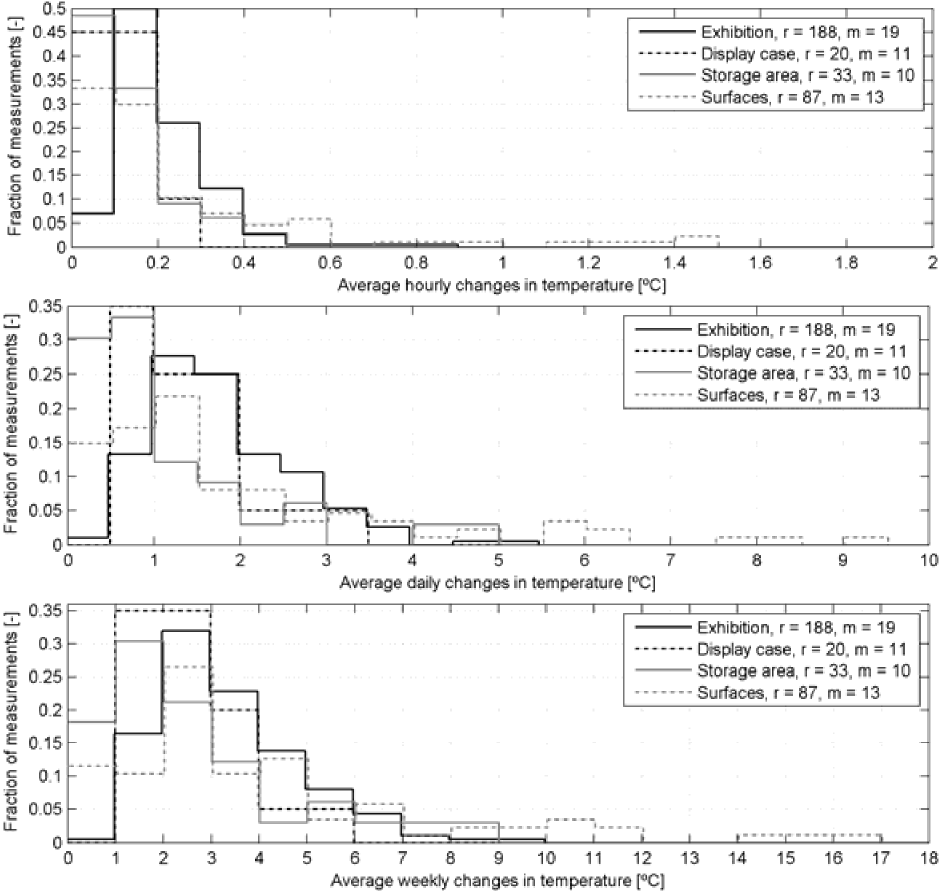


Figure 4.3: Average short changes in temperature, hourly (top), daily (middle) and weekly (bottom).

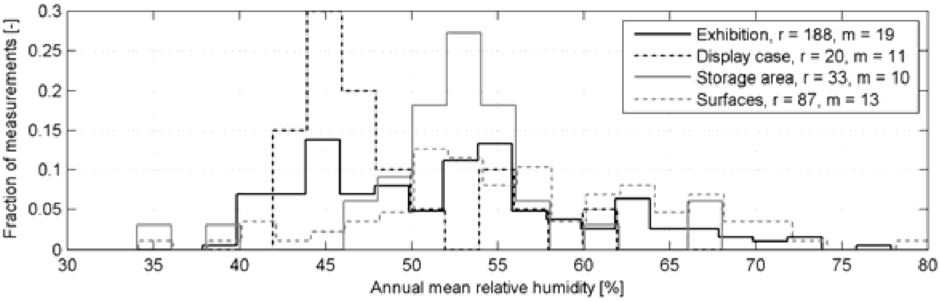


Figure 4.4: Annual mean relative humidity.

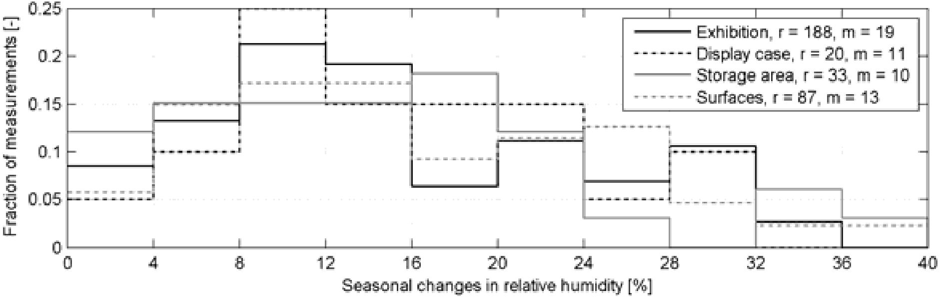


Figure 4.5: Seasonal adjustments in relative humidity.

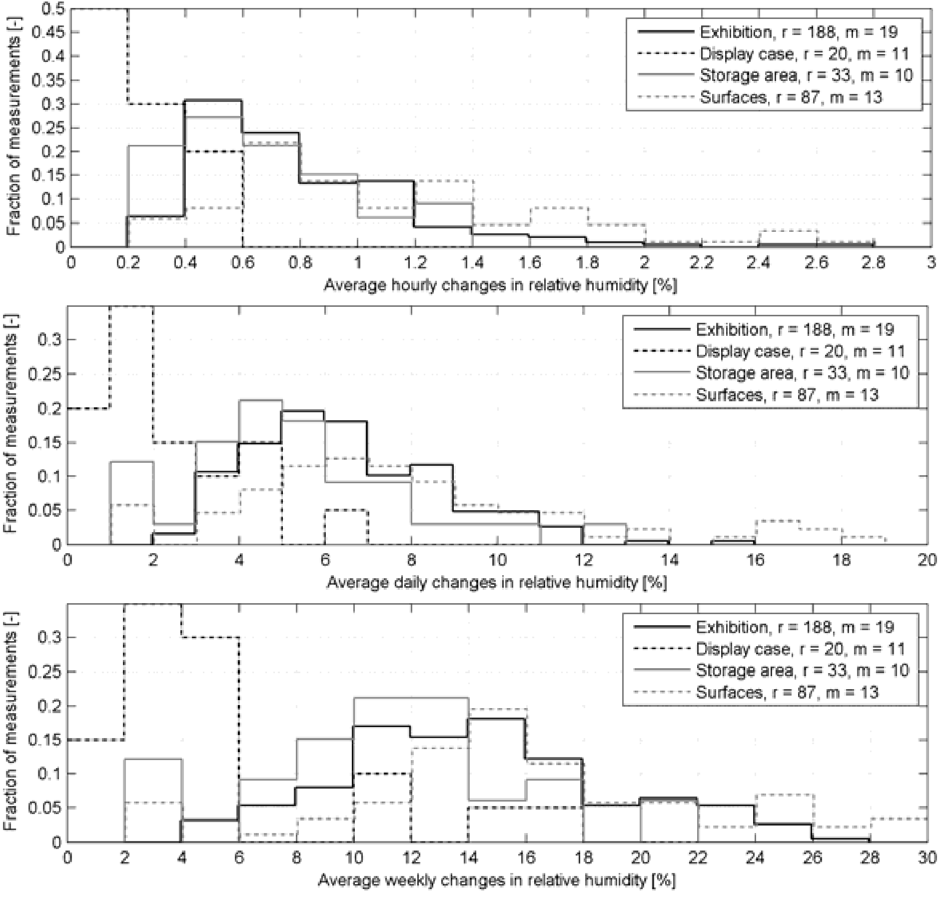


Figure 4.6: Average short changes in relative humidity, hourly (top), daily (middle) and weekly (bottom).

Surface temperatures show a similar (wide) spread as exhibition room temperatures. The average temperature, however, is lower. This is caused by the lack of insulation in most envelopes; winter surface temperatures are low and therefore also the annual mean is affected.
Seasonal adjustments in temperature, caused by either natural or forced (by a climate system) behavior, are displayed in figure 4.2. Between storage areas and exhibition rooms no significant differences in range are observed. Display cases, however, show less adjustment to the seasons. This is, again, due to the fact that few cases are placed in non-heated rooms; temperature buffering capacity of display cases is usually very small. Surfaces show a larger seasonal change than room temperatures (fewer measurements at low changes and more at higher changes).

Temperature fluctuations shorter than seasonal are displayed in figure 4.3. A distinction is made in average hourly changes, average daily changes and average weekly changes. Hourly changes are calculated by taking the difference between minimum and maximum for each hour. For daily and weekly changes, a period is used of 1 day and 1 week respectively. This also means that hourly changes are always smaller than or equal to daily changes and that daily changes are always smaller than or equal to weekly changes. Again exhibition rooms, display cases, storage areas and surfaces are displayed separately. The largest fluctuations occur near surfaces and in exhibition rooms; display cases and storage areas are usually more constant in temperature. There is not much difference between positions; the spread in each group is quite large.

Figure 4.4 shows the annual mean relative humidity. Again the largest differences occur in exhibition rooms: average relative humidities of 38 to 77% occur. Storage areas show average values more in the middle range of 50 to 60% – a range that is required in most museum program of demands. Also display cases show a smaller range, but average RH is lower than in storage areas. The average RH in cases will resemble the average RH in the room the case is placed in. In most museums these rooms are not controlled in terms of RH.

Figure 4.5 shows seasonal adjustment in relative humidity. These seasonal changes are either caused by differences in set points or by the naturally occurring climate. Differences between exhibition rooms, display cases and storage areas are negligible.

In figure 4.6 average short changes in relative humidity are displayed. Hourly changes are quite small; all positions score below 3%RH/h. In display cases average hourly changes are below 1%RH/h. Exhibition rooms are less constant than storage areas. Weekly changes in display cases are smaller than daily changes in other areas: the bulk of display cases is below 6%RH/week while most storage areas show changes around 8%RH/day! This clearly shows the buffering effect of cases, as mentioned by Padfield [1996].

When climate data is sorted by QoE (remember: Quality of Envelope; 1 is the lowest quality and 4 the highest; see Chapter 2.1.4) and LoC (remember: Level of Control; 1 is no control and 4 is full control; see Chapter 2.1.4) simultaneously, statistical results can be displayed as in figure 4.7. Temperatures are displayed in dark grey, relative humidities in light grey. A double temperature and RH scale is presented; the annual means (Tm and RHm) correspond to the higher numbers, hourly (dTh and dRh), daily (dTd and dRd), weekly (dTw and dRw) and seasonal changes (Ts and RHs) to the lower numbers. The mean value is displayed as a bar, the minimum and maximum values are displayed as lines indicating the spread for each bar.

The annual mean temperature is lowest for QoE 1 & LoC 1: 14ºC. In LoC 2 and 3, temperatures are usually well over 20ºC, while in LoC 4 the average temperatures are very close to or slightly below 20ºC. This makes sense, since in LoC 4 the air temperature is controlled directly, while in LoC 2 and 3 the air is heated by combinations of convection, conduction and radiation and is controlled less precisely. Moreover, in LoC 4 the air can also be cooled during warm periods.

The annual mean RH is highest in QoE 1 & LoC 1: 65% average RH for 41 rooms. In LoC 2 the RH drops to an average of about 45%. This is mainly due to the fact that temperature and RH are coupled (see e.g. the psychometric chart in figure 2.5); increasing T leads to a decreasing RH when not changing the moisture content of the air. In LoC 3 and 4 this moisture content is changed (by humidifying and/or dehumidifying), average RH values are in between 50 and 55%RH.

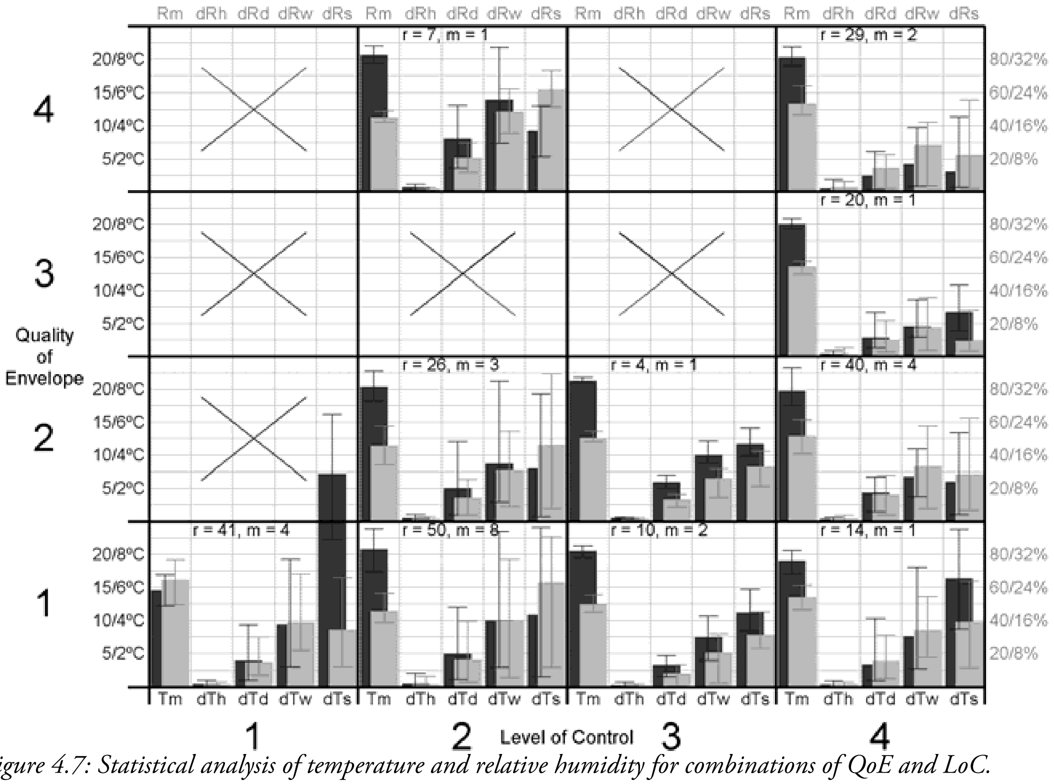


Figure 4.7: Statistical analysis of temperature and relative humidity for combinations of QoE and LoC.

Hourly changes are small in all museums. Average changes hardly exceed 0.5ºC/hour and 3%RH/hour. It is surprising to note that those changes are highest in QoE 1 & LoC 2 and also in QoE 4 & LoC 4. In the first case this is caused by weather influences and visitors; in the latter case by the climate system that shows a switching behavior.

Average daily changes are highest in QoE 4 & LoC 2 and lowest in QoE 3 & LoC 4; on average these changes are in between 1 and 3 ºC/day and 3 to 8%RH/day. Again, the difference between the various combinations of QoE and LoC is small; the spread in range (for each combination) is usually much larger than the differences in average values between the combinations. This means that more stable and less stable indoor climates are not just a matter of building and climate system, but also depend on other factors e.g. building use. Also the exact measurement position is of influence.

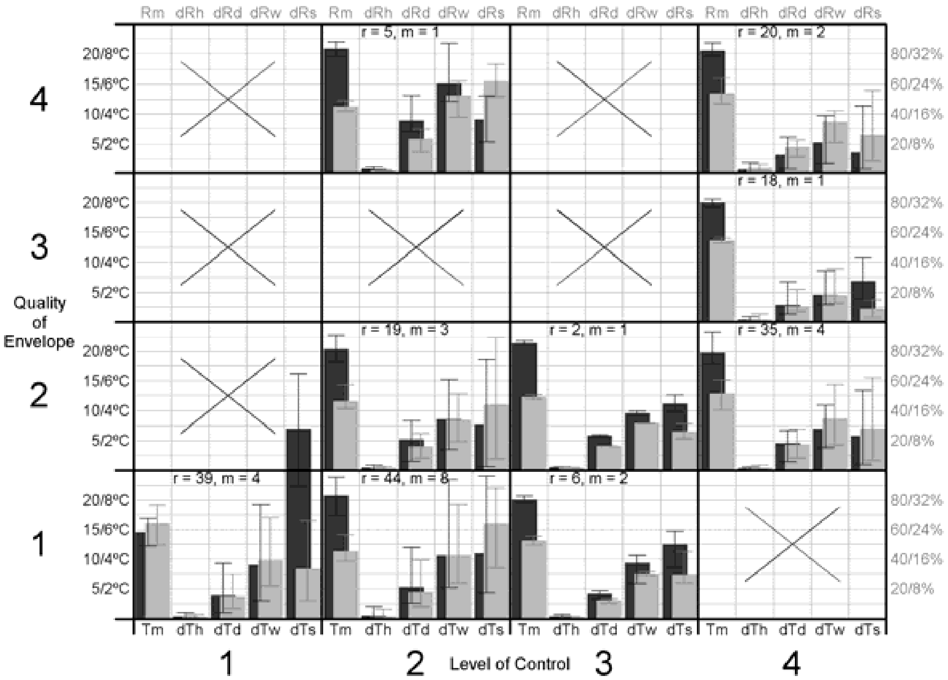


Figure 4.8: Analysis of T and RH for combinations of QoE and LoC, exhibition rooms only.

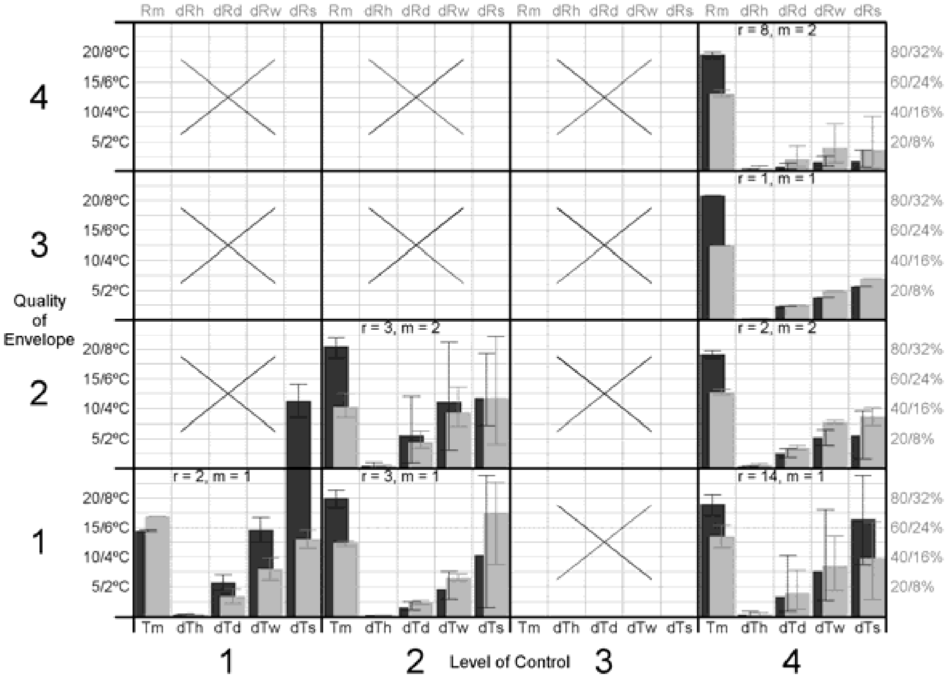


Figure 4.9: Analysis of T and RH for combinations of QoE and LoC, storage areas only.

Weekly changes in T and RH are lowest in QoE 3 & LoC 4 and highest in QoE 4 & LoC 2. In museums with less climate control, weekly changes are higher than in more controlled museums. This is also the case with seasonal changes: over a whole year changes get smaller in a more controlled building. This does, however, depend on the climate strategy: it might be beneficial to apply some seasonal changes to better preserve building and objects and save energy, as will be discussed in chapter 7.

When the data is split into exhibition rooms only (see figure 4.8) and storage areas only (figure 4.9) the main thing that is noticed is that in LoC 4 the short changes in T and RH are reduced. This means that the disturbing effect of visitors on the indoor climate cannot be minimized completely using a climate system. Only in storage areas, in which no visitors are allowed, the climate is most stable.

4.1.2. General climate risk assessment method for measured indoor climates

Results obtained using the general climate risk assessment method (see Chapter 3.2.2) for all permanent measurements are displayed in figures 4.10. Figure 4.10 shows the average amount of time each climate class is met (grey bars), as a percentage of the measured period, for each combination of QoE and LoC. Also minimum and maximum values are displayed (spread in each bar). The best average scores are in QoE 3 and LoC 4; the worst scores are encountered in QoE 1 and 4 in combination with LoC 2.

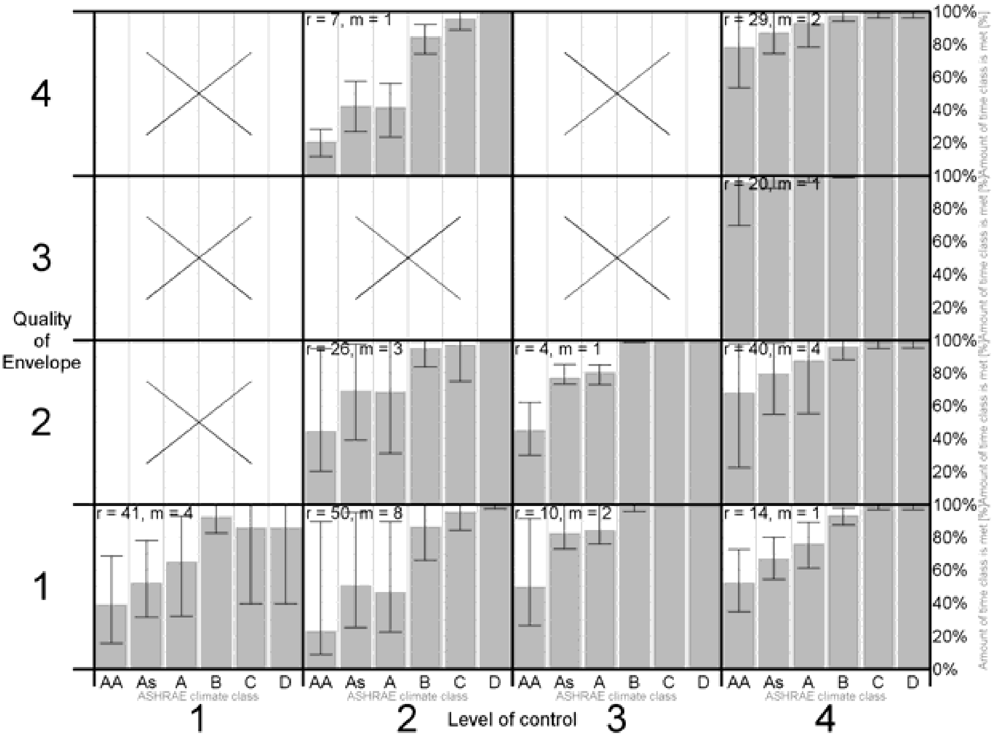


Figure 4.10: Average, minimum and maximum percentage of measured time in each ASHRAE climate class for combinations of QoE & LoC.

The difference between LoC 1 and 2 is obvious: due to heating class C and D obtain a better score (less moist conditions), but all other classes score worse due to the drop in RH under winter conditions. With humidity control (LoC 3), this negative effect can be avoided, obtaining results that resemble or outperform LoC 1 results. Only LoC 4 in combination with QoE 2, 3 and 4 are able to increase ASHRAE scores considerably. This implies that installing an advanced climate system is nonsense if the monumental building envelope is not improved. Moreover, comfort heating in museums increases risks for collection and building unless it is combined with a proper RH control system and an improved envelope.

When zooming in on LoC 4 only, QoE 3 – the improved envelope – shows the best results, but this is based on 1 museum only. Interestingly, QoE 2 and 4 perform very similar – though not as good as QoE 3 – although newly built museums and slightly changed old monuments differ considerably in construction. This can be explained by looking into the design and maintenance process for the individual museums. The museum with QoE 3 has staff members that care about the indoor climate and carefully monitor the performance of the climate system and make changes if needed. The performance of museums with QoE 2 is limited due to the building envelope. In the museums researched with QoE 4, the climate system is not monitored properly and has a very instable control strategy; the system still is in its original setup, without being fine tuned to e.g. building use.

It is difficult to decide which ASHRAE climate class is met. A 100% match to a certain class is hardly ever reached in practice. Maybe when a class is reached for 95% of time (or more), the risks for the objects are still conform that class. This depends, however, on what actually happens in the other few percent the class is not met. An RH that is slightly too low for a few hours gives another risk than a sudden very low RH due to system failure. Climate classes are not really suitable for assessing risks unless a class is met all the time.

More important than knowing the percentage of time measurements comply with each class, is to know what happens during the time these measurements do not meet the class.
As discussed in chapter 3, a climate class is defined as a bandwidth around a running average value that follows the seasons, both for T and RH. The class is not met when either T or RH are out of their bandwidth. This can be a coincidence: RH could have been high in the first place and a slight temperature drop could make the RH move out of the bandwidth. But also structural problems can be the cause: e.g. a seasonal change in RH is encountered while this is not allowed in a class. Figure 4.11 shows for each class the possible reasons and the percentage of positions that qualify for each reason. This is done by comparing the calculated seasonal changes and periodic changes (using the statistical operations) to the maximum values allowed for each climate class (table 3.1). Only positions that do not comply with a class for 2.5% of time or more are included.

As can be seen in figure 4.11, the main reasons ASHRAE climate class AA is not reached are: seasonal RH changes too high (100%), weekly RH changes too high (95%), weekly T changes too high (83%) and daily RH changes too high (70%).
Class As is not met because weekly RH changes are too high (96%), weekly T changes are too high (85%) or daily RH changes are too high. Interesting to see is that in 1/3 or all cases seasonal RH changes are too high, while As allows a seasonal change of ± 10%RH.

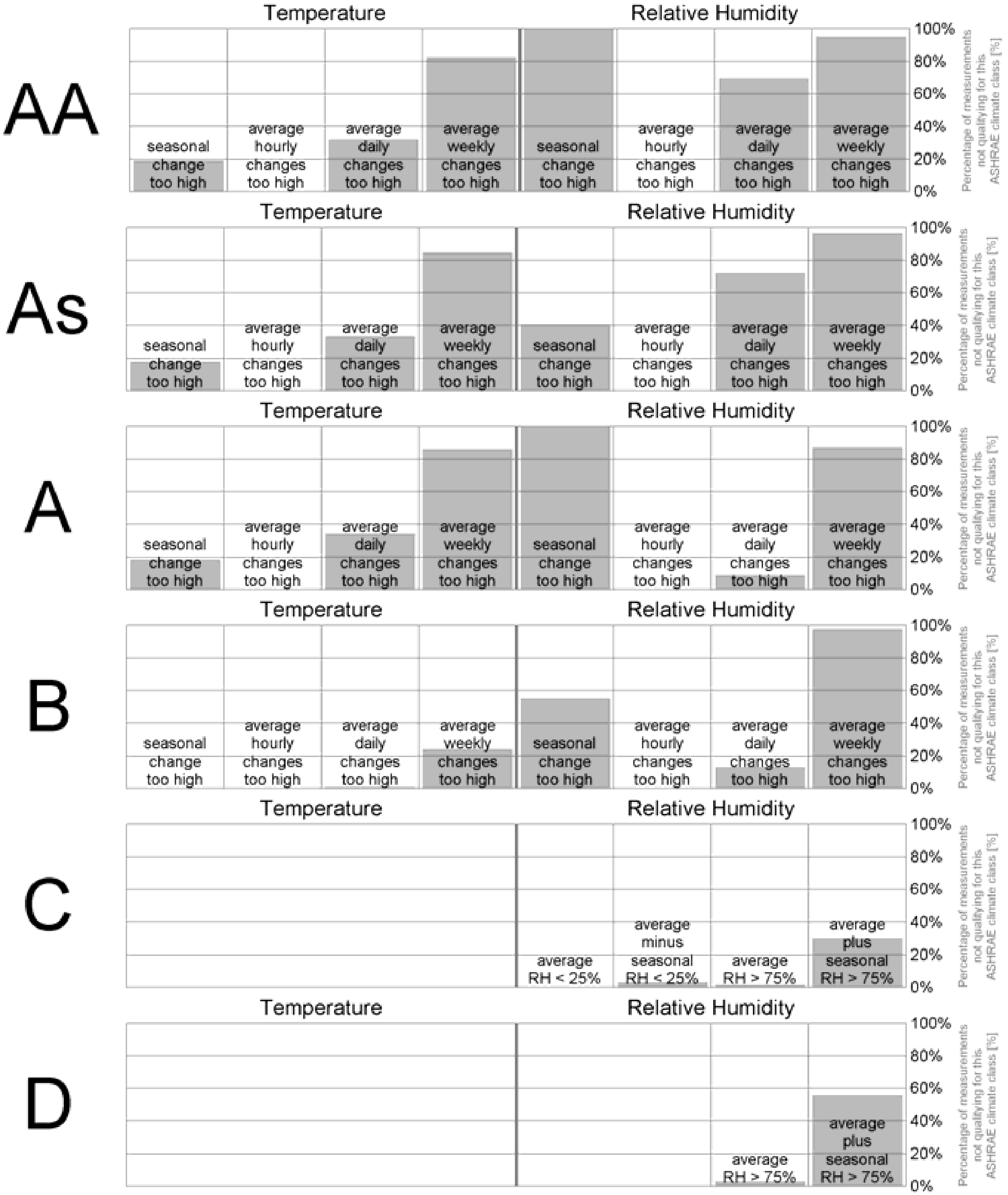


Figure 4.11: Reasons why climates do not meet the ASHRAE AA, As, A, B, C and D climate class.

The main reasons for not meeting class A are: seasonal change in RH too high (100%), weekly changes in RH too high (87%), weekly changes in T too high (86%).

For class B the main reasons are too high weekly RH changes (98%) and seasonal changes in RH too high (45%).

For class C and D, few positions have an average RH that is too low or high (only 1 position has an average over 75%RH). 20 positions have an average plus a seasonal rise that exceed 75%RH, while 2 positions have an average minus a seasonal drop that are below 25%RH. This means that all other positions not in accordance with C or D show short fluctuations that exceed 75% or go below 25%RH.

When combining all reasons mentioned, it is clear to see that seasonal changes in RH and average weekly changes in RH are the main causes for not complying with the ASHRAE classes. It is strange to notice that most museums, however, put a maximum value for hourly and daily changes in their program of demands but forget to imply weekly changes. In chapter 5 will be explained that most objects do not even respond to hourly or daily RH changes.

4.1.3. Conditions close to building surfaces

On 87 positions (on a total of 241) also surface temperatures of the building have been measured. The RH is calculated using the same humidity ratio as in the room the surface is located in. These local climates are in some cases experienced by the objects, because in most museums objects are placed near building surfaces.

Figure 4.12 displays statistical properties of these local climates near surfaces. When this figure is compared to figure 4.7, it can be noticed that the spread is much larger; the maximum values are very high. Some museums show daily temperature changes larger than 10ºC. This is mainly due to the fact that some surfaces experience direct solar radiation and are rapidly heated. In some museums lighting causes high local surface temperatures.

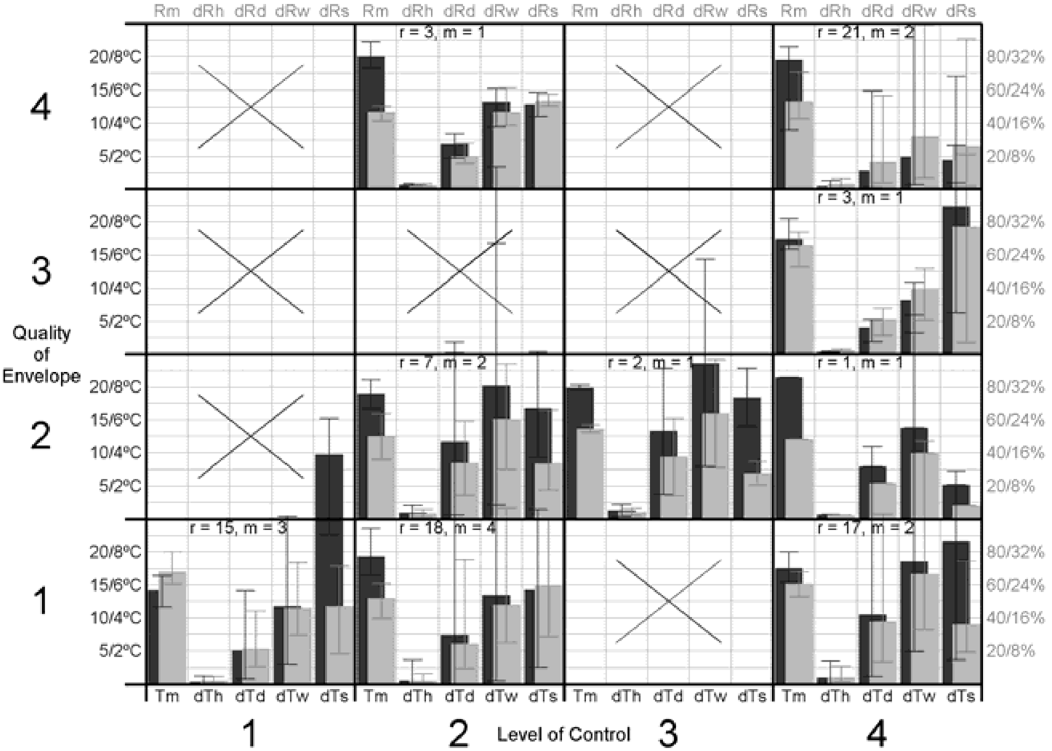


Figure 4.12: Analysis of statistical parameters for combinations of QoE and LoC, surfaces only.

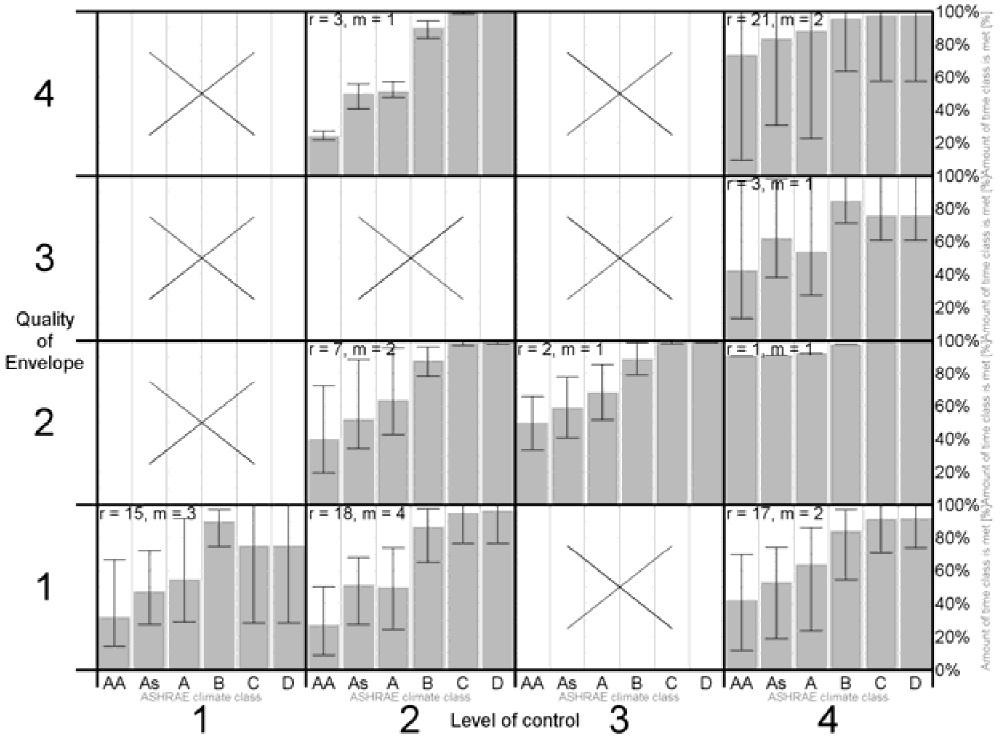


Figure 4.13: Analysis of general climate risks for combinations of QoE and LoC, surfaces only.

In all museums average seasonal changes in temperature are much higher near the surface than in the room. Because of the lack of insulation, temperatures near the envelope can become quite low during winter. Also the RH changes accordingly; higher seasonal changes are noticed. In some cases also the yearly average RH is much higher: up to 10%RH when compared to air conditions.

Figure 4.13 provides the general climate risk assessment results for surfaces. When this graph is compared to figure 4.10, it is not easy to see many differences. Some combinations of QoE and LoC have a higher score near surfaces than in the middle of the room; others show an opposite behavior.

4.2. DATA ANALYSIS OF SPECIFIC PROBLEMS OCCURRING IN MUSEUMS

In this part specific effects are described that have occurred and led to problems in some museums. Each situation is described briefly and differences between average room climate and local climate are shown and explained.

4.2.1. Conditions near walls

Several museums are housed in monumental buildings. Often the original building envelope was not changed over the years; there is e.g. no insulation present. Conditions near such a wall are different from average room air conditions. Even in case of a very advanced climate system, local differences are very hard to avoid without changing the envelope.

Figure 4.14 shows a Climate Evaluation Chart (see chapter 2) for the indoor climate in the middle of the room (left) and near the old envelope (right). In the room temperatures remain in between 17ºC and 22ºC; RH usually is kept in between 50% and 60%. The envelope is of QoE 3, with an extra wall on the inside, but this wall is not airtight thus allowing the indoor air to reach the original stone wall. The right graph shows that temperatures near the original stone wall are in between 5ºC and 24ºC. The RH, calculated out of the humidity ratio of the room conditions, shows values up to 100% during autumn and winter: values over 100% are not possible and result in condensation. Apparently stone is not a suitable nutrition source for fungi; although mould growth was expected here it was not encountered in practice. Nevertheless this position is not suitable for displaying objects: table 4.1 shows that the percentage in each climate class drops considerably (class AA during 99% of time in the room and only 17% near the surface). It might also pose a threat to the building (water might wet the wall and result in frost damage or mould elsewhere) and it cools and dehumidifies the indoor air.

In buildings without (de)humidification – LoC 1 or 2 – this is an entirely different situation. Figure 4.15 shows 2 CEC's: the left graph represents the indoor climate in the middle of room 5 in museum 20, while the right graph displays conditions near the surface of a thick wooden door in the north façade. Temperatures in the room are similar to the temperatures in the previous example, but because no humidification is used the RH drops to lower values during winter: weekly averages of 30% are encountered. Near the cold surface of the door temperatures drop to nearly freezing conditions, but the RH close to the surface does not come close to an RH of 30%: even in winter the RH is about 50%. Moreover, the RH near the door shows less variation over the year that the RH in the room! When looking at the ASHRAE percentages (table 4.1), differences are small. The room has a marginally higher score on all classes except AA.

Both examples show that risks to a building not only depend on the building construction, but also on climate systems and set points.

Table 4.1: Percentage of time ASHRAE AA, As, A, B, C and D are met in 2 rooms and near 2 envelopes.

Position	ASHRAE climate class					
	AA	As	A	B	C	D
M12 R15 room	99	99	100	100	100	100
M12 R15 envelope	17	51	35	83	66	66
M20 R05 room	26	58	55	94	99	100
M20 R05 envelope	31	40	52	83	98	98

4.2.2. Blinded windows

Museum 12 is of QoE 3; a double wall is used as an extra barrier between the indoor climate and the original envelope. To increase the amount of exhibition space, some windows are hidden behind this extra wall; from the outside only a dark screen is visible. Direct solar radiation hits the screen once a day, for about an hour. Temperature in the cavity rises quickly; the effect is clearly noticeable just in front of the extra wall. In room 22 a panel painting is placed in front of this blinded window. Temperature and humidity are measured in between painting and wall as displayed in the right CEC in figure 4.16. In room

25 the average room conditions are measured; these data are displayed in the left CEC. The right CEC shows that in spring and summer temperatures rise very fast to about 29°C; the RH drops to values of 35% simultaneously.
Table 4.2 shows that the percentage of time the ASHRAE classes are met decreases considerably for classes AA, As and A.

This example shows that unexpected effects can happen when changing an envelope. Moreover, these effects are difficult to notice: only with infrared thermal imaging this 'heated' blinded window was spotted by accident.

Table 4.2: Percentage of time ASHRAE AA, As, A, B, C and D are met in the room and near a blinded window.

Position	ASHRAE climate class					
	AA	As	A	B	C	D
M12 R22 room	99	99	99	100	100	100
M12 R25 surface	76	85	89	98	100	100

4.2.3. Inlet air conditions

Some climate systems distribute air to rooms in order to improve the indoor climate. Inlet air is supposed to heat or cool and to humidify or dehumidify. This means that the air distributed to the room does not have the same specifications as the room climate: temperature is lower or higher and humidity mixing ratio is higher or lower, depending on the output of the building management system (BMS). Objects placed near inlet vents will experience a climate that is totally different from the room climate. Figure 4.17 shows a CEC of the average room climate in a storage room (left) and also the inlet air conditions (right). The indoor climate is very constant at 20°C and 50%. In order to keep conditions that way, the inlet air ranges from 16°C to 22°C and the RH is in between 40% and 65%. The BMS uses a constant humidity mixing ratio for the inlet air: all inlet air conditions appear as a vertical line in the right CEC.
Table 4.3 shows that especially class AA is met less frequent near the inlet: 70% of time when compared to 100% of time on other positions in the storage area.

Table 4.3: Percentage of time ASHRAE AA, As, A, B, C and D are met in room and near inlet.

Position	ASHRAE climate class					
	AA	As	A	B	C	D
M18 R04 room	100	100	100	100	100	100
M18 R04 inlet	70	94	97	100	100	100

4.2.4. Displacement ventilation

In some museums displacement ventilation is installed. This is a full air system that is based on buoyancy differences: cool fresh air is distributed on floor level; this air is heated by people so that it rises and people breathe the fresh air. Polluted, warm air is extracted high in the room. This is a principle normally used in office buildings with enough sources to heat up the cool inlet air, e.g. people, computers and printers. In museums it is not very common, because of a different use: few people are present in museums compared to

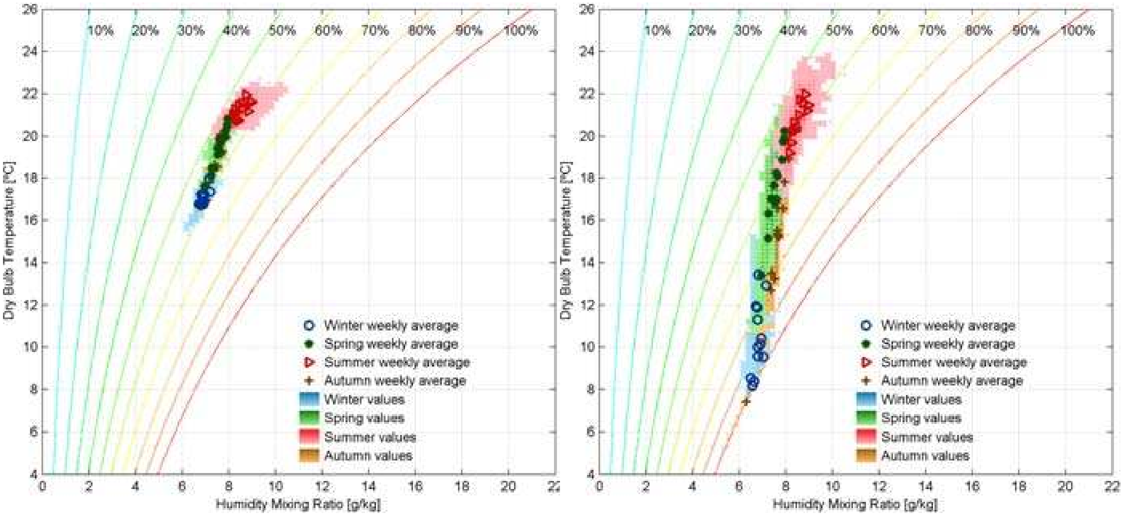


Figure 4.14: CEC of room 15 in museum 12 (left) and near the envelope of room 15 in museum 12 (right) behind an extra internal wall.

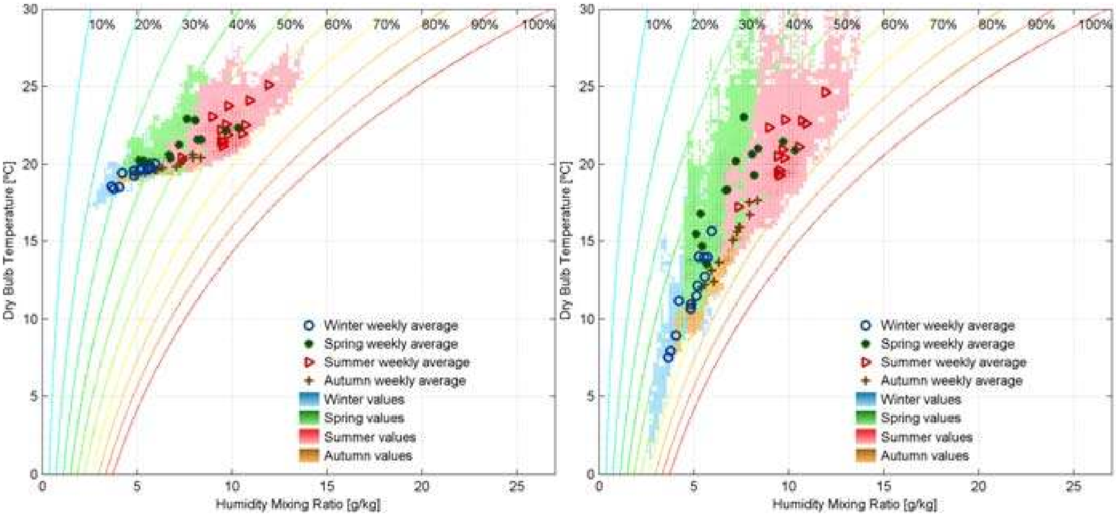


Figure 4.15: CEC of room 5 in museum 20 (left) and near the envelope of room 5 in museum 20 (right).

offices and also less equipment that produces heat is used so the cool air remains on floor level longer. That is why, in this museum, this system is combined with radiator heating. Cool air enters the room (also in winter; in figure 4.19 it is clear to see that inlet air conditions are always colder than indoor air conditions; the colored clouds of measured values in the right graph shows much lower values than the clouds in the left graph), is heated by people and radiators, mixes slightly with the air present in the room and is then extracted close to the ceiling. Gradients in a room normally need to be avoided, but this system works because of these gradients. A large object (e.g. a 2 meter high statue) placed on the floor might experience 21°C and 50% at the top and 15°C and 75% at the bottom: very high gradients that might cause damage. According to table 4.4, the amount of time in climate classes AA up to B decreases near the inlet conditions.

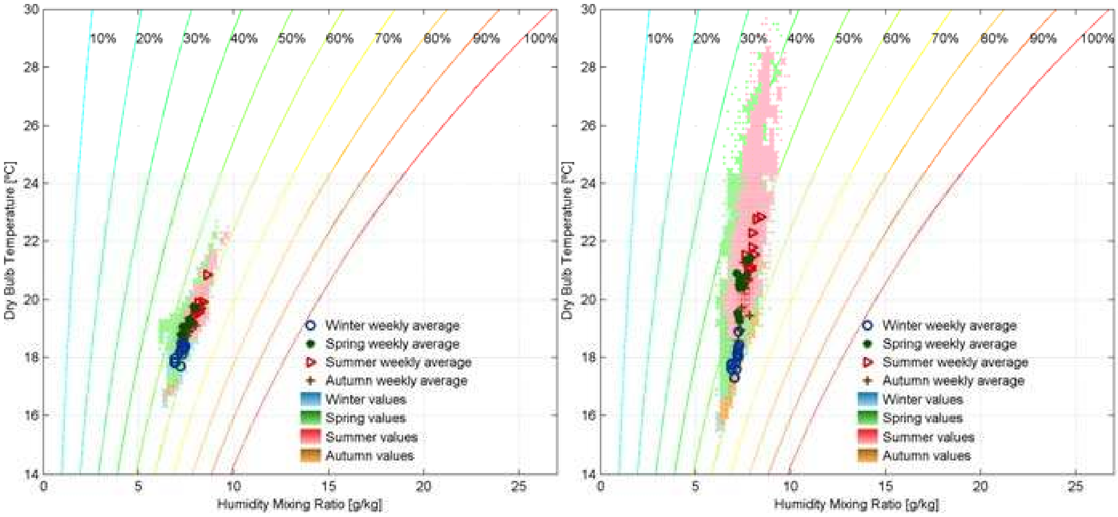


Figure 4.16: CEC of indoor climate in museum 12 room 25 (left) and local conditions in room 22 (right) caused by a blinded window.

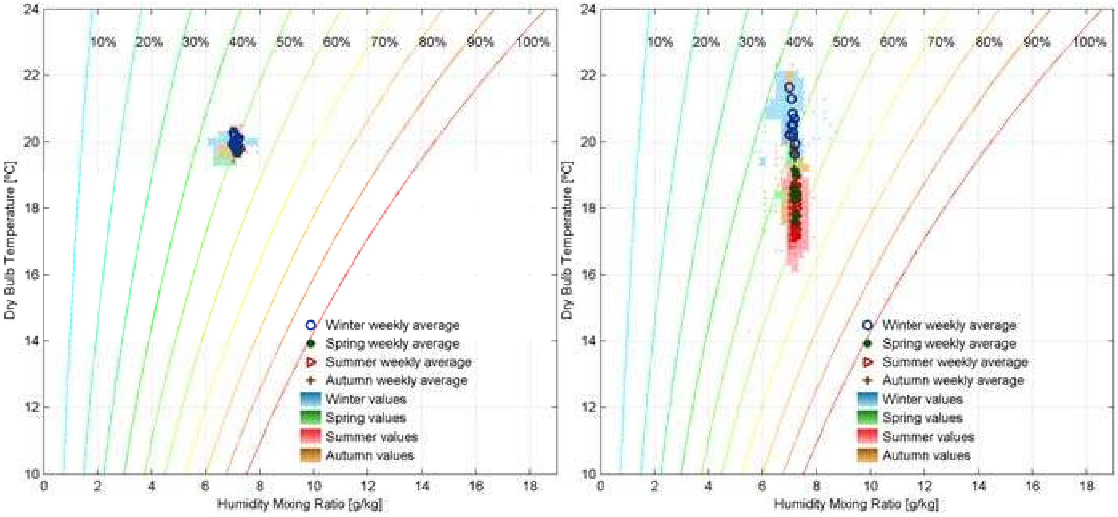


Figure 4.17: CEC of museum 18 room 4 indoor climate conditions (left) and inlet air conditions (right) caused by a full air system.

This example shows that displacement ventilation is not usable in museums because of the gradients that are created, both in temperature and relative humidity.

Table 4.4: Percentage of time ASHRAE AA, As, A, B, C and D are met in room and inlet.

Position	ASHRAE climate class					
	AA	As	A	B	C	D
M07 R11 room	74	80	90	95	100	100
M07 R11 inlet	34	64	65	88	100	100

4.2.5. Stratification

Museum 17 is a storage building with rooms about 12 meters high. The climate system is an air heating system: hot water is distributed to a fan powered heat exchanger; heated air is blown into the room. Figure 4.20 shows a CEC of the indoor climate at a height of 1.5 meters (left) and at 10 meters (right). Temperatures at 10 meters are up to 12°C higher than at 1.5 meters. The largest differences occur during the heating season: winter weekly averages are in between 17°C and 19°C, while at 10 meters 21°C to 24°C occur. RH drops to dangerously low levels: less than 10% is recorded. For a storage room in which wooden objects are stored this is not an ideal environment. Also table 4.5 shows very low percentages for classes AA, As, A.

Table 4.5: Percentage of time ASHRAE AA, As, A, B, C and D are met at 1.5 and 10m height.

Position	ASHRAE climate class					
	AA	As	A	B	C	D
M17 R07 room 1.5m	28	56	56	92	99	100
M17 R02 room 10m	12	27	24	74	89	100

4.2.6. Display case effects

In many museums display cases are used to protect delicate objects. Many types of cases are used, but the principle of a small amount of air, well buffered by collection or hygroscopic material does wonders for stabilizing the indoor climate.

Figure 4.21 displays a CEC of the indoor climate in museum 16 room 1 (left) and a CEC of the microclimate in a buffered display case (right). This room is heated only; large temperature stratification occurs during winter because floor and walls are not insulated. The display case is situated on the floor, where it is slightly cooler – especially during the heating season. Silica gel is used to buffer the RH; it is placed in a drawer in the base of the display case. The right CEC shows that although temperatures range from 17°C to 26°C, the RH remains fairly constant within 48% to 53%.

In figure 4.22, 2 CEC's are shown. The left CEC displays the indoor climate in museum 13 room 3. This monumental building (QoE 1) with heating and local humidification has temperatures in between 16°C and 24°C, while the RH is within a range of 28% to 63%. The collection in this room is placed in very old display cases filled with books. The microclimate in one of the cases is displayed in the right CEC in figure 4.22. Temperatures are similar to the room climate (a bit warmer during autumn and winter), but the RH is quite constant: values in between 40% and 51% are noted and a yearly cycle is clearly visible: the weekly averages show a circular shape while the spread in measured values is very narrow.

In table 4.6 the percentages each ASHRAE climate class is met are displayed. Both display cases have much higher percentages than the rooms surrounding the cases. These examples show that display cases provide a stable climate to the collection. This is only valid for cases which contain hygroscopic material to buffer RH; this can be the collection itself or an added buffer material.

Table 4.6: Percentage of time ASHRAE AA, As, A, B, C and D are met in 2 rooms and 2 display cases.

Position	ASHRAE climate class					
	AA	As	A	B	C	D
M16 R01 room	19	51	40	83	94	100
M16 R13 display case	90	90	90	100	100	100
M13 R03 room	31	76	76	96	100	100
M13 R05 display case	92	99	99	100	100	100

4.2.7. Visitor impact

Visitors produce heat and moisture. Half of the heat and moisture is produced by breathing, the other half by transmission through the skin (sweat). In case no cloakroom is available also moisture is added to the indoor air by entering the museum with wet coats.

Museums with LoC 1 (no systems available) show very little impact by visitors: figure 4.18 shows temperature and relative humidity during a week; daily peaks in temperature in the visited room (R06, light grey), while in the non-visited room (R03, dark grey) no daily peaks are visible. The RH however does not show peaks; the behavior in both rooms is similar. This is due to the fact that each visitor produces heat and moisture simultaneously: temperature and humidity mixing ratio rise, but the RH remains fairly constant. Near the building envelope temperature is more constant due to the thermal mass of the masonry construction; the light grey dotted line shows only a small increase in surface temperature. Therefore the RH near the surface rises rapidly; +5% in just one hour on April 16th.

These short time fluctuations do not have a huge effect on the ASHRAE percentages: table 4.7 shows hardly any differences between rooms and surfaces.

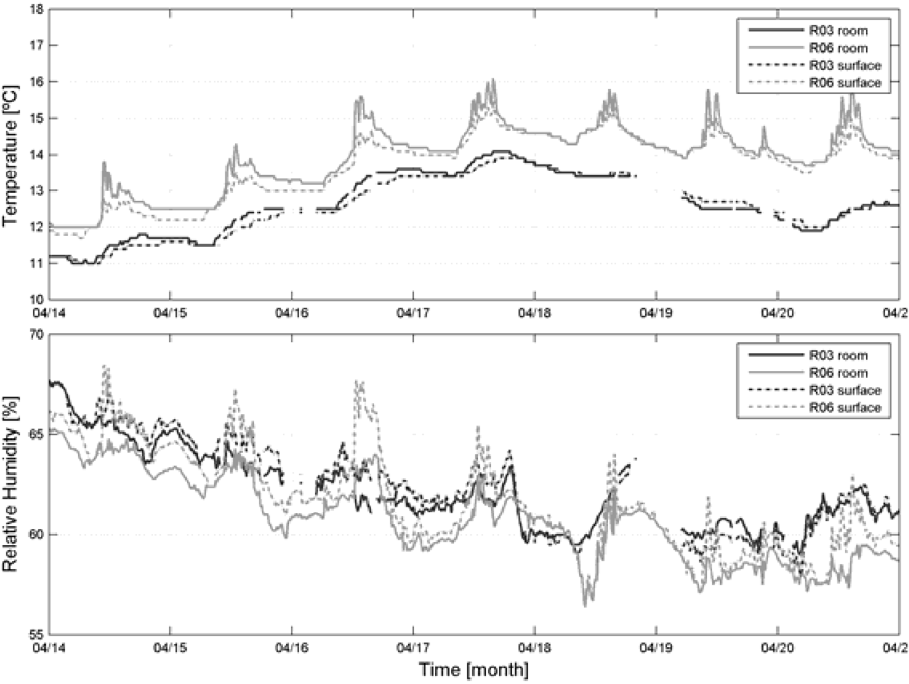


Figure 4.18: T and RH versus time in museum 5 room 3 (non-visited) and room 6 (visited).

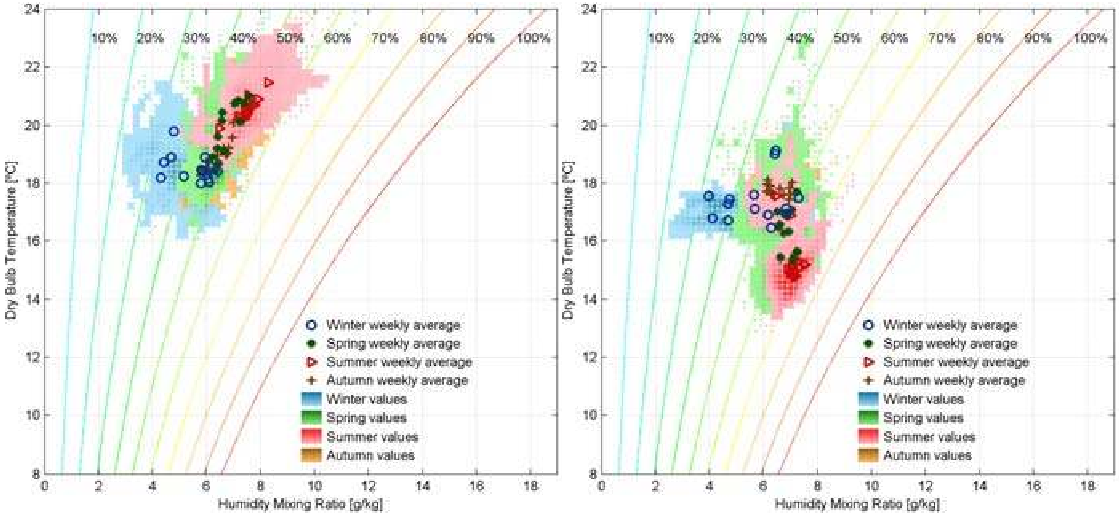


Figure 4.19: CEC of museum 7 room 11 indoor climate (left) and air inlet conditions (right) as an example of a displacement ventilation system.

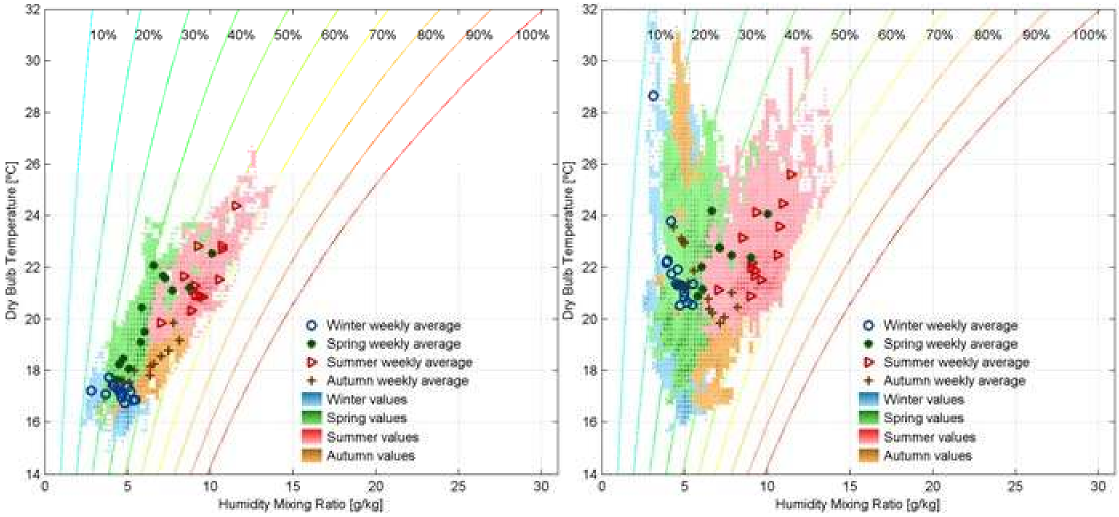


Figure 4.20: CEC of museum 17 at 1.5 m height (M17R07, left) and at 10 m height (M17R02, right) as an example of stratification.

Table 4.7: Percentage of time ASHRAE AA, As, A, B, C and D are met in 2 rooms and near 2 internal walls.

Position	ASHRAE climate class					
	AA	As	A	B	C	D
M05 R03 room	47	63	72	97	92	92
M05 R06 room	60	68	81	98	99	99
M05 R03 surface	46	63	72	97	92	92
M05 R06 surface	58	66	80	97	98	98

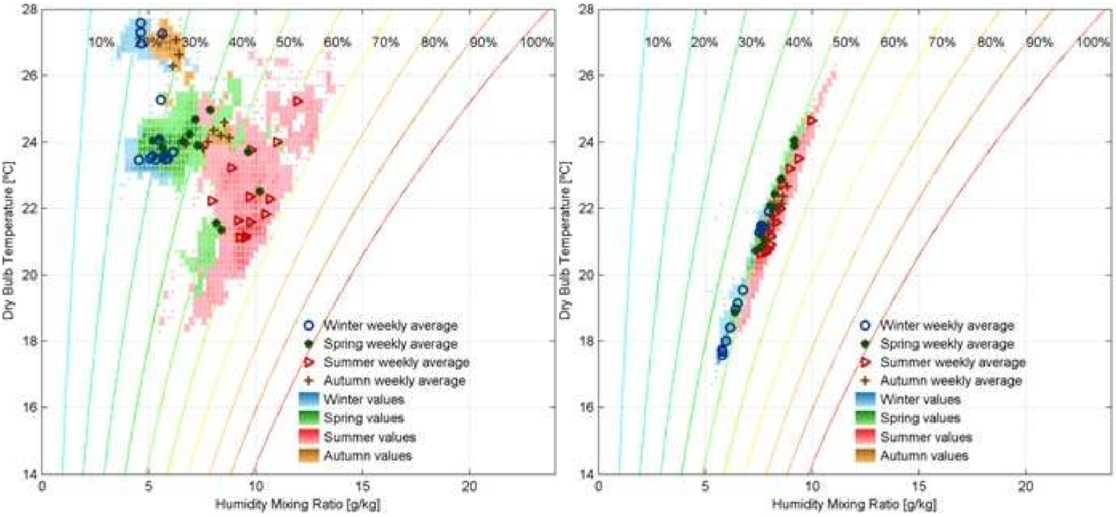


Figure 4.21: CEC of museum 16 room 1 indoor climate (left) and display case conditions (right).

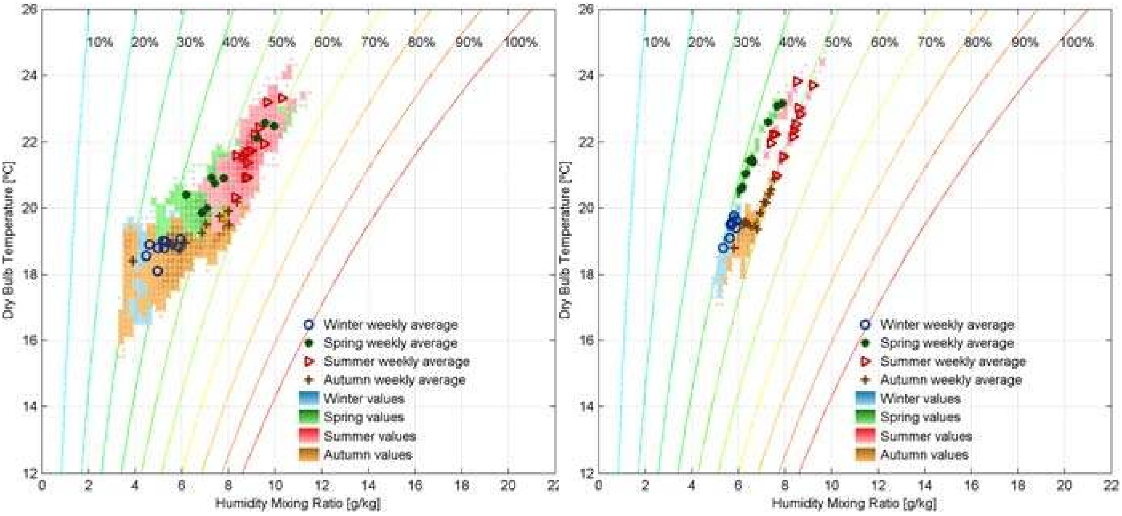


Figure 4.22: CEC of museum 13 room 3 indoor climate (left) and display case conditions (right).

4.2.8. Set points

Set points have an effect on preservation and on energy use. By changing the set point, preservation can be improved and/or energy can be saved.

In museum 12 previously a temperature set point of 19°C in winter and 20°C in summer was used. During the night the climate system was turned off; the building was allowed to cool to 17°C. The RH was kept between 55% and 60%. The dark grey curves in figure 4.23 show the effect of these set points during the year 2005; summer overheating (temperatures much higher than the set point temperature) is visible at the end of May and halfway in June. The RH dropped to 45% a few times in April and May. These deviations were mainly due to lack in capacity, which led to system malfunctions.

The museum changed the set points to follow the outdoor climate: 19°C in winter and 21°C during summer. The RH is kept lower than before: in between 52 and 58%. At night the system was not switched off but it remained functional at a lower capacity. The resulting indoor climate, measured in 2009, is displayed in light grey in figure 4.23.

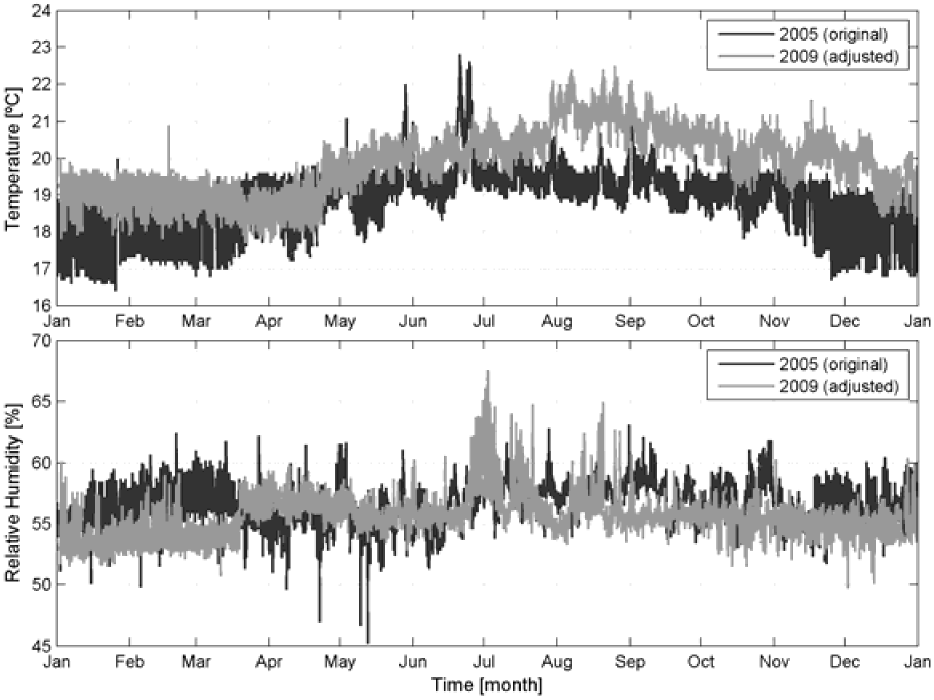


Figure 4.23: Indoor climate in Museum 12 room 25 in 2005 (original) and 2009 (adjusted).

Table 4.8: Percentage of time ASHRAE AA, As, A, B, C and D are met in 2005 and 2009 (Museum 12, room 25).

Position	ASHRAE climate class					
	AA	As	A	B	C	D
M12 R25 room 2005	99	99	99	100	100	100
M12 R25 room 2009	98	99	100	100	100	100

The adjusted set point leads to less energy use and less installation failure because peak loads are reduced. In Chapter 7 this subject is described in more detail.

4.3. CONCLUSIONS AND RECOMMENDATIONS

Heating to comfortable temperatures causes the RH to drop to very low values during winter, creating serious risks to collections. Adding humidification to minimize these dry conditions helps in improving risks for the collection, but might put the monumental building envelope at risk. Only in new buildings or in physically improved buildings heating and humidification is a good option.

Risks to collections and to the building do not depend much on the type of building envelope, but mainly on the choice for a climate system and the set points used for this system.

Near the monumental envelope climates differ from the average room climate. In heated buildings the climate near the envelope is usually safer for the objects and the building, because winter RH values do not drop as low as elsewhere in the building. In humidified buildings risks near the envelope might be high, depending on the set points of both temperature and RH. Also the building might get damaged because of mould growth or wood rot in or on the construction of the façade.
A climate system, even a very advanced one, cannot exclude differences in climate caused by weather effects near an old envelope.

Each museum and climate system demands a certain amount of attention of the user. Monitoring and adjusting is always required, even in fully automated systems. The best results are obtained in museums in which the staff is involved and a synergy between building, objects, systems and indoor climate exists. It is essential to fine tune each system during normal use of the museum.

A museum is not an office. Climate systems that function very well in offices may not function in museums at all. In offices, maintaining a constant RH is not an important issue and also large differences exist in how museums and offices are used, e.g. in terms of people per floor area.

The Dutch situation shows little seasonal change in set points, both on temperature and relative humidity. This is, however, allowed in ASHRAE: small seasonal changes are expected not to harm objects. A seasonal temperature change is helpful in minimizing energy use; moreover less effort is needed to keep the RH within the desired bandwidth. Changing set point is therefore a great opportunity to optimize museum climates while saving energy; chapter 7 will go deeper into this topic.

Climate classes are not really suitable for assessing risks unless a class is met all the time. A 100% score on ASHRAE B can be less risky for an object than a 95% score on class AA, depending on the climate during the 5% of time class AA is not met. This is also the main limitation for climate classes: risks provided for each class are only valid when the indoor climate meets the class all the time. Of course, the ASHRAE climate classes are meant to be a design guideline; not to classify or quantify risks to objects.
The most common reason for a climate not to comply with a certain ASHRAE climate class is that midterm variations, in between seasonal and daily, in relative humidity are too large.

Average room conditions are not representative for the climate objects experience in case of large local differences. Knowledge of indoor climates in buildings is essential for proper preservation of objects. Also here, staff is very important: when one knows its building, exhibitions can be planned with the building's limitations in mind.

Specific climate risk assessment 5

Chapter 3 discussed statistical operations to characterize the indoor climate. Also the general climate risk assessment method was introduced. In this chapter, another approach is proposed. This specific climate risk assessment method takes into account the actual response of museum objects to the indoor climate. The goal of this new method is to better predict the risks to objects and to provide easy to interpret output.

5.1. INTRODUCTION

The methods used in chapter 3 are not the most suitable to assess risks to objects. The statistical operation expects a lot of knowledge from the user, while risks predicted by the general climate risk assessment method are only valid when the indoor climate is within the corresponding ASHRAE climate class during 100% of time. This chapter proposes a new risk assessment method, in which for four typical objects degradation risks are estimated.

Since most guidelines should be applied to a mixed collection with varying objects of different susceptibility and value, four typical objects – considered as representatives of collection susceptible to climate degradation – are presented in paragraph 5.1.1. Objects are needed that are well defined, that represent part of most mixed collections in museums and that already were researched in the past.

5.1.1. Paper

Paper is a common material, especially in archives. Also in museums many paper objects are present, such as books, etchings, maps and playing cards. In figure 5.1 some paper objects are displayed. For paper, the most important degradation processes are mould growth and chemical degradation (yellowing of paper, fading of colors). Chemical degradation of paper is often called aging and has been researched by Zou [1996a & 1996b] and Porck [1999].

5.1.2. Panel paintings

Painted wooden panels (see figure 5.2) consist of various materials: different types of wood, hide glues, gesso composed of glue and gypsum or chalk and different kinds of paint and varnish. Paint itself can include wax, egg tempera, oils or combinations of these. Therefore painted wooden surfaces vary in complexity [Michalski, 1994a].

In its tangential direction, wood shows the most dimensional changes when responding to changes in relative humidity. When assessing damage, the worst case scenario should be taken into account, so it is vital that strain developed in this direction is examined [Michalski, 1994a].

Figure 5.1: Example of a display case with books and framed etchings on the background (left) and another display case with single sheets of paper and a book in a leather cover (right).

Figure 5.2: Example of a panel painting: 'Jonge moeder' by Gerrit Dou (1658); oil paint on an 8 mm wooden panel (top and side view; frame removed).

Figure 5.3: Example of furniture: Japanese lacquer box photograph and construction drawing [V&A website].

Figure 5.4: Example of wooden statues: varnished (left) and polychrome (right).

5.1.3. Furniture

The Japanese lacquer box is an example of a very delicate piece of furniture. This box (figure 5.3) was made in 1640. It is subject of research in the Victorian and Albert museum in the UK. It was completely restored; its physical properties were examined by Bratasz et al. [2008]. Lacquer undergoes a considerable dimensional response on the absorption of moisture which was shown to be nearly identical to that of the Hinoki wood in the radial direction. Therefore the wood in the lacquer and the box work in nearly the same way.

There are two areas of restraint in the box. The first restraint corresponds to assemblies of cross-grained wooden elements (see figure 5.3, right). Secondly the lacquer is fully restrained in the direction parallel to the grain of the wooden panel it is glued to.

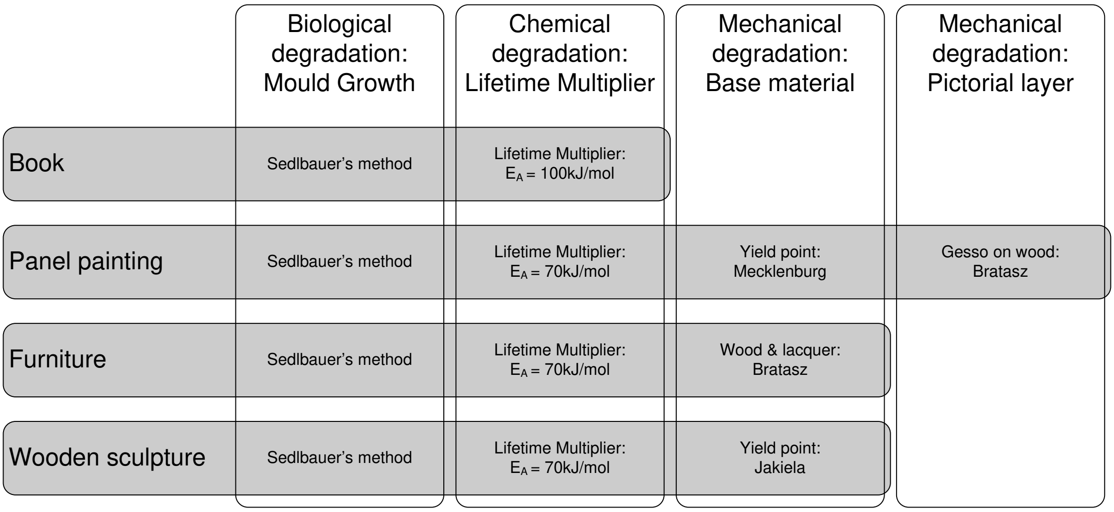
5.1.4. Wooden sculptures

Wooden sculptures are made of one or several pieces of wood, which can be of various types. Most wood carvings are solid. Decorative layers, if applied, are usually thin and open to water vapor. Two examples of wooden statues are displayed in figure 5.4.

The main problem regarding statues is a gradient over the wood. The outer layer responds fast to changes in relative humidity while the core responds very slowly. Differences in moisture content between core and surface cause stresses in the material. Cracking might occur if stress levels become too high.

5.2. SPECIFIC CLIMATE RISK ASSESSMENT

The degradation principles – as mentioned in Chapter 3 – are applied to the four specific objects of the previous paragraph. Each combination of object and degradation principle is assessed separately. Figure 5.5 provides an overview; the rest of this paragraph is used to explain these combinations.



	Biological degradation: Mould Growth	Chemical degradation: Lifetime Multiplier	Mechanical degradation: Base material	Mechanical degradation: Pictorial layer
Book	Sedlbauer's method	Lifetime Multiplier: $E_A = 100\text{kJ/mol}$		
Panel painting	Sedlbauer's method	Lifetime Multiplier: $E_A = 70\text{kJ/mol}$	Yield point: Mecklenburg	Gesso on wood: Bratasz
Furniture	Sedlbauer's method	Lifetime Multiplier: $E_A = 70\text{kJ/mol}$	Wood & lacquer: Bratasz	
Wooden sculpture	Sedlbauer's method	Lifetime Multiplier: $E_A = 70\text{kJ/mol}$	Yield point: Jakiela	

Figure 5.5: Assessment of climates on object level.

5.2.1. Response time

Response time is defined as the time needed for an object to get to 95% of the end value in case of a step change in RH. Figure 5.6 provides an example. The light grey line represents a step change from 40%RH to 60%RH on January 1st. The black line shows the response for an object with a response time of one week (black): after a week 95% of the step change (59%RH) is reached. The dark grey line shows the response using a response time of one month (30 days), while the dotted black line corresponds to a response time of a season (91 days).

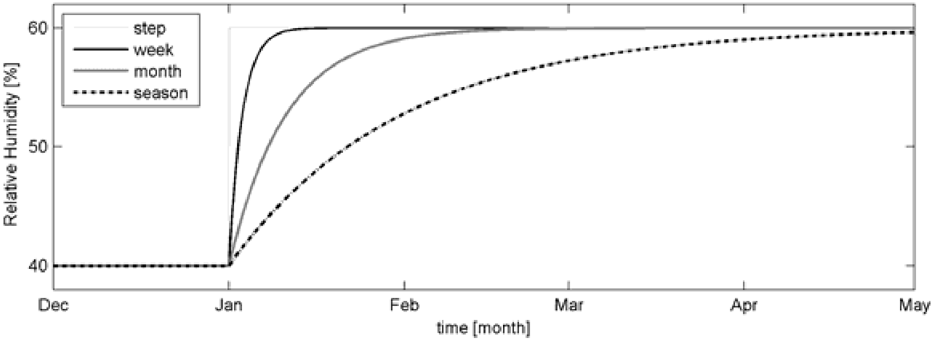


Figure 5.6: Example of one week response, one month response and 3 month response to a step change.

To obtain the climate experienced by the object, the response is approximated using a first order filter; formula 5.1 displays the equation of the object's response, which is only valid for data series with a constant time interval and represents the first order approximation.

$$RH_{response,i} = \frac{a \cdot RH_i + a^2 \cdot RH_{i-1} + a^3 \cdot RH_{i-2} + a^4 \cdot RH_{i-3} \ldots}{\frac{a}{1-a}} \tag{5.1}$$

In which:

$RH_{response,i}$	Object response in Relative Humidity [%]
RH	Relative Humidity [%]
i	Current data point in the data range [-]
a	Response factor [-]

The response factor is determined using equation 5.2:

$$a = e^{\frac{-3\cdot\Delta t}{\tau_{response}}} \tag{5.2}$$

In which:

a	Response factor [-]
Δt	Time interval between 2 successive data points [s]
$\tau_{response}$	Response time [s]

When a is small – the response time is much larger than the time interval – formula 5.2 is approximated by $1 / (1 + \Delta t/\tau)$. The RH response on time i can then be calculated out of the previous RH response and the current RH. This is displayed in formula 5.3:

$$RH_{response,i} = \frac{RH_{response,i-1} + \dfrac{RH_i}{n/3}}{1 + \dfrac{1}{n/3}} \tag{5.3}$$

In which:

$RH_{response}$	Object response in RH [%]
RH	Relative Humidity [%]
i	Current data point in the data range [-]
n	Number of data points in response time [-]

Figure 5.7 shows the result when using measurement data instead of a step function. The original measurement RH data (museum 5, room 3) is plotted in light grey; running averages – again with a period of a week, a month and a season – are also plotted. Larger response times have lower maximum values and higher minimum values, reducing the total bandwidth of RH. Also peaks appear later than in the original signal; the season response (black, dotted) shows its maximum in September which is a few weeks later than the original signal.

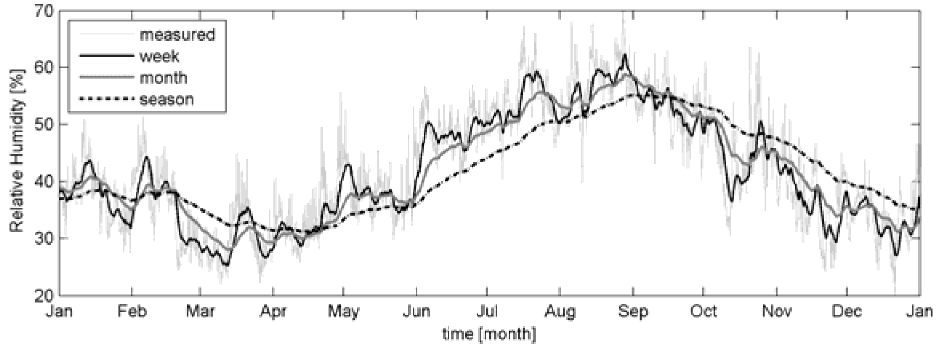


Figure 5.7: Example of one week response, one month response and 3 month response to measured RH.

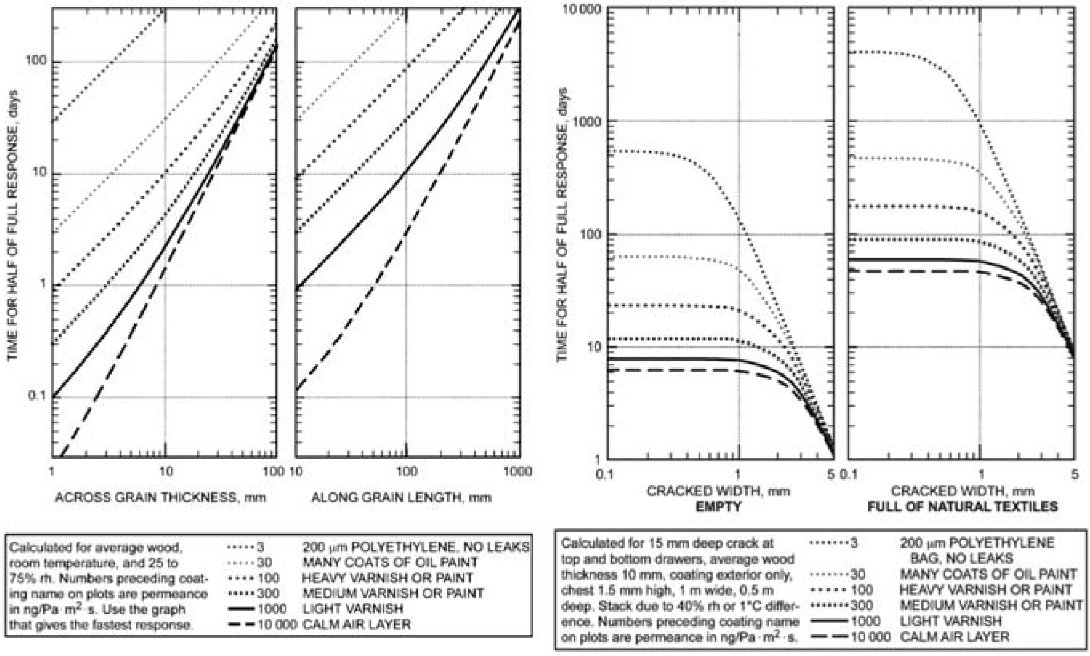


Figure 5.8: Time for half of full response for average wood (left) and a chest with air openings in the top and bottom drawers [ASHRAE, 2011].

Figure 5.8 shows times for half of full response for average wood with different types of coatings. The left graphs show the response of the wooden panels, while the right graphs show response of a chest with drawers that have a small opening at the top and bottom. These graphs can be used to estimate response time, but because half of the full response is displayed, which is the time needed to get to 50% of a step change in RH, the value in the graphs has to be multiplied by 4.32 (ln 0.05 / ln 0.5) to obtain the 95% response time.

For paper objects and opened books, response time ranges from hours to three days [Michalski, 1993]. A single sheet of paper responds in minutes [Michalski, 1993] while a book that is placed in a closed cabinet has a response time of 6 to 9 months [ASHRAE, 2007]. In order to assess the worst case, a response time of minutes is used.

The response time of panel paintings depends on the thickness of the panel and on the layers on the panel. The center of a 1 cm thick piece of wood that is oil painted and varnished (heavy varnish or paint) on one side only has a hygroscopic halftime of 5 to 6 days. In order to find this value in figure 5.8, one should consider a thickness of 20 mm and a calm air layer (figure 5.8 assumes equal surface treatment on all sides of the wood). This corresponds to a response time of about 26 days. Near the painted surface (just under the varnish or paint) the halftime is about 1 day, corresponding to a response time of 4.3 days. The backside of the painting has, in some cases, a faster response: if the wooden panel is untreated and in close contact with the indoor air a response time of 10 hours is to be expected. In case of a somewhat closed backside (e.g. using bees wax), the front panel determines the response time.

For the lacquer box, the lacquer acts as an additional barrier for the wooden panel under the lacquer, slowing down moisture diffusion, thus minimizing the risks of short fluctuations in RH. Risk on damage because of full response by drying or wetting of the entire panel remains. According to Bratasz, the lacquer provides the same barrier as an additional layer of wood of 26 mm on both sides of the panel [Bratasz et al, 2008]. According to figure 5.8, 26 mm bare wood leads to a halftime of 10 days, which corresponds to a response time of about 40 days.

Wooden sculptures often have a light varnish or thin polychromic layer. Half of full response of the surface of such a sculpture is 0.1 days (figure 5.8), leading to a response time of about 10 hours. Vici [Vici et al., 2006] researched a 40 mm wooden object. He concluded that after 15 days the deformation of the wood is at its maximum; the most harmful strains occur therefore using a response time of 15 days.

Table 5.1: Relevant responses and corresponding response times for four objects.

Object	Relevant response(s)	Response time	Reference
Paper	Full response of single sheet	minutes	Michalski, 1993
Panel painting	Surface response just under oil paint Full response of entire panel	4.3 days 26 days	ASHRAE, 2011 ASHRAE, 2011
Lacquer box	Full response of entire lacquer box	40 days	Bratasz et al., 2008
Wooden sculpture	Surface response Sub-surface response causing maximum stresses	10 hours 15 days	ASHRAE, 2011 Vici et al., 2006

The response times mentioned in table 5.1 are only valid for undamaged objects. Cracks in the decorative and/or protective layer will cause the object to react faster to changes in RH.

Response times are only used for relative humidity. For temperature, response times are very short, so temperature changes are assumed to be instantaneous [Jakiela et al., 2008].

5.2.2. Mould growth

Fungi develop on the exterior parts of objects. For risk analysis of fungal growth local climates around objects are assessed. This means that for fungal growth response times of materials do not play a role; measured temperatures and relative humidities close to objects are assessed directly.

For mould growth prediction, the curves provided by Sedlbauer (see Chapter 3, figure 3.2) are used, which are based on fungi common in buildings. Two independent calculations are performed. The first calculation is for building surface type I. This is a surface that in itself functions as nutrition for fungi. The second calculation is for type II surfaces. These surfaces have a porous structure; nutrients are stored in these pores (e.g. as dust).

First germination is calculated. For each measured temperature the RH corresponding to each germination curve is calculated. The measured RH is compared to these calculated RH values. As soon as one curve is exceeded a counter starts: the mould germination factor is determined. This is the total continuous period of exceedance of a curve divided by the time for spore germination specified for that curve, e.g. after exceedance of the 8-day curve for 8 successive days the value is 1. The third graph of figure 5.9 shows this. As soon as a value of 1 is encountered – it does not matter which curve caused this – the spores germinate and are now able to grow.

For each combination of T and RH after germination the growth rate is determined (again using figure 3.2). This growth rate is an integer between 0 and 5. The fourth graph of figure 5.9 shows the result. Finally the bottom graph shows the total summation of these growth rates. The outcome is the total amount of mycelium growth in millimeters during the measured period. If this amount is more than zero there is a high risk on fungal growth.

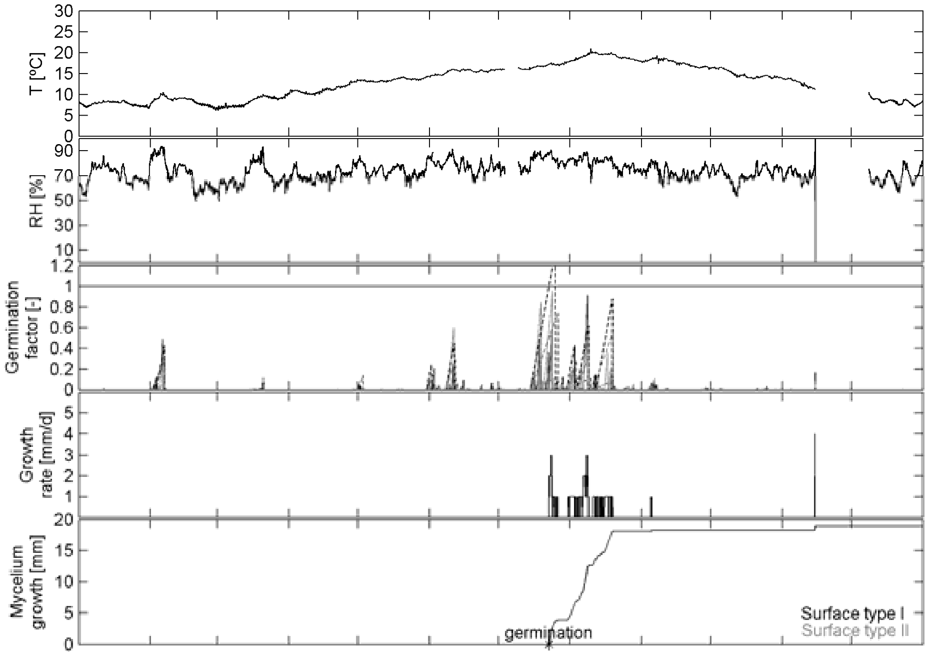


Figure 5.9: Measured temperature over time (top graph) and relative humidity over time (second graph), calculated germination factor (third graph), calculated growth rate after germination (fourth graph) and total mycelium growth (bottom graph) for surface type I and II.

5.2.3. Chemical degradation

For the four objects mentioned in paragraph 5.1.1 calculation of chemical degradation is done using the Lifetime Multiplier, as introduced in formula 3.2 in chapter 3. For paper an activation energy of 100 kJ/mol is used while for the other objects 70 kJ/mol is more appropriate. The input RH for formula 3.2 is determined by incorporating surface response time using formula 5.3.

Figure 5.10 displays temperature (top), relative humidity (middle) and LM (bottom, for paper objects using an activation energy of 100kJ/mol) over time for Museum 5 room 3. Also the mean LM is displayed.

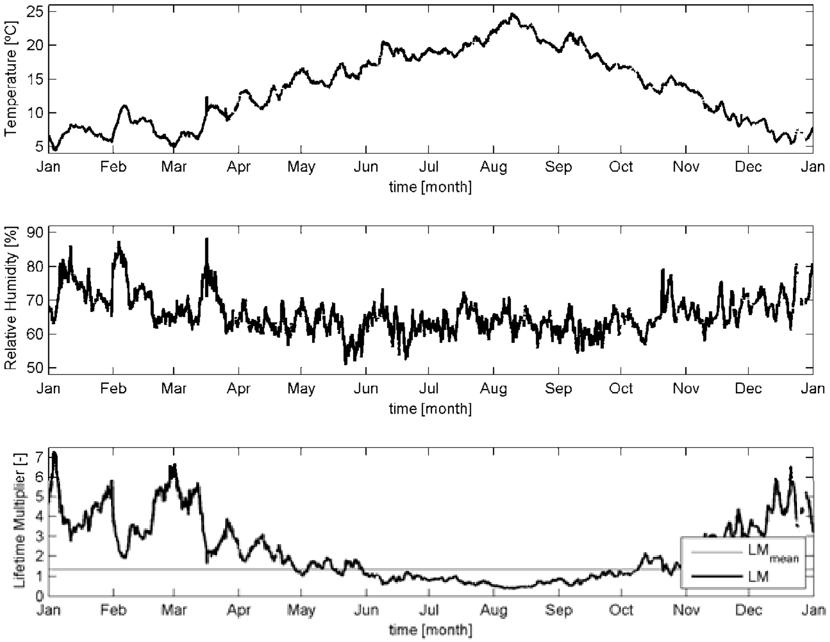


Figure 5.10: Lifetime Multiplier, calculated out of the T and RH data of museum 5 room 3, for paper objects.

5.2.4. Mechanical degradation

Mechanical degradation can be split into 2 different processes. The first process is degradation caused by the method of construction of the object: degradation due to dimensional changes in the object's base materials. This can either be caused by a varying equilibrium RH of the bulk over time or by differences between surface and bulk in thicker objects. The second process is mechanical degradation in between the base material and the pictorial layer, caused by uneven dimensional changes of the object's base material and the pictorial layer.

The second process is only valid for objects that consist of a separate construction and design layer. For the four objects in this thesis, only panel paintings quality for this second process.

Paper

For paper objects mechanical damage caused by temperature and humidity changes is not very important. Dry conditions cause paper to become brittle, but damage only occurs when handling the object, not by the changing properties in itself.

Panel paintings

For panel paintings, mechanical damage caused by gradients is assessed by determining whether yield occurs. Mecklenburg's graph (Chapter 3, figure 3.5) is used. The axes in Mecklenburg's graph show starting RH and ending RH because a step response was researched. When dynamic RH values are assessed, surface response RH is used as ending RH and full response RH as starting RH. Mecklenburg's graph is symmetrical except for the 'failure' line: the panel painting will show cracks at the surface when the surface RH drops to a low value (and shrinks) while the full response RH remains at the original value longer. In contrast, when the surface RH rises to a high value (and expands) cracks will not appear instantly because the surface material is under compression.

Figure 5.11 shows Mecklenburg's graph with the axis labels changed as explained above. The left graph shows predicted behavior of the wooden panel; the right graph shows the corresponding risks. If this behavior is elastic only, no damage is expected: the panel painting is safe. If plastic behavior is noted, deformation occurs which might lead to damage eventually: damage is possible. The failure region shows the area in which damage is likely.

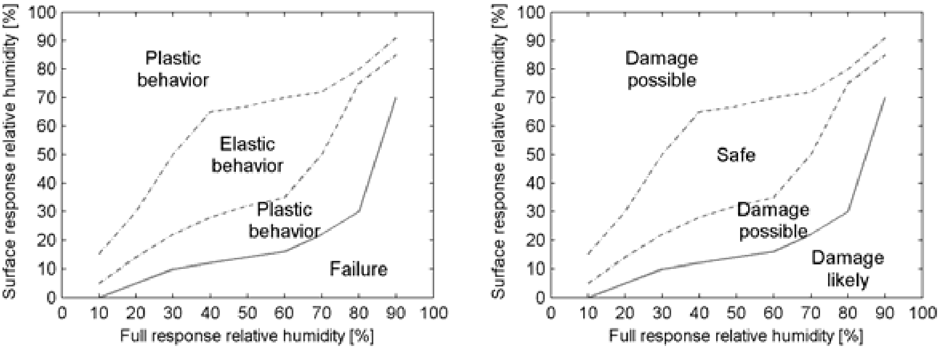


Figure 5.11: Surface response RH versus full response RH: mechanical behavior (left) and risks for mechanical damage (right) for a panel painting [based on Mecklenburg et al., 1994].

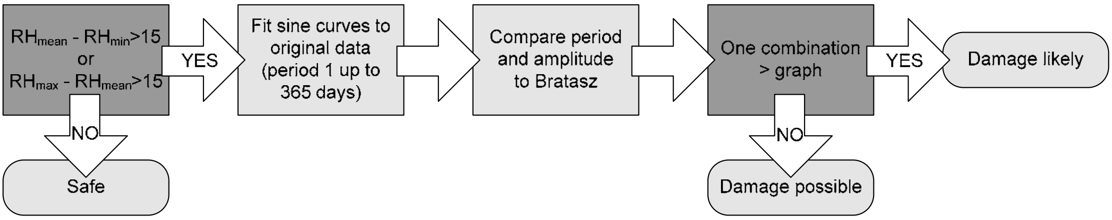


Figure 5.12: Assessing full response RH over time to determine mechanical degradation of the object's structure.

For damage to the pictorial layer Bratasz's curve (Chapter 3, figure 3.9) is used. This demands a more thorough approach. As can be seen in figure 3.9, no damage occurs for changes in RH smaller than 15%RH, independent from the duration of RH change. This is the first check that is performed: see whether differences in full response RH over time exceed 15%RH. If not, the object is safe. If 15%RH is exceeded, further analysis is necessary. In order to use Bratasz's graph, sine curves need to be extracted from the RH data. Sine curves are fitted to the full response RH data. Amplitudes and periodic shifts are determined, periods, however, are preset. These periods start with a length of 365 days; each next period is √2 shorter (258 days etc.) until a period of 1 day is reached. Each combination of period and amplitude is assessed using Bratasz's graph. If one combination exceeds the 'gesso on 10mm of wood, deformation considered' curve, the object damages over a century. If, however, none of the signals exceeds the curve, the object might still be damaged over the years. At the moment it is not possible to assess a combination of different sine signals simultaneously. Figure 5.12 provides an overview of the analysis stated above.

Furniture

For the lacquer box a similar approach is used as for panel paintings, but now full response RH and annual mean RH values are used. The left graph of figure 5.13 [Bratasz et al., 2008] is used to check strains in the material: the solid grey curves display the 0.004 yield lines for wood while the dotted lines represent 0.004 yield for lacquer. Elastic behavior is allowed, while plastic behavior might cause damage. Curves for lacquer and wood need to be combined to prevent damage in both materials; the right graph in figure 5.13 shows the safe area in which no permanent deformation occurs. The influence of the lacquer is only noticed in the high humidity area (>80%); the safe region narrows at these high RH values.

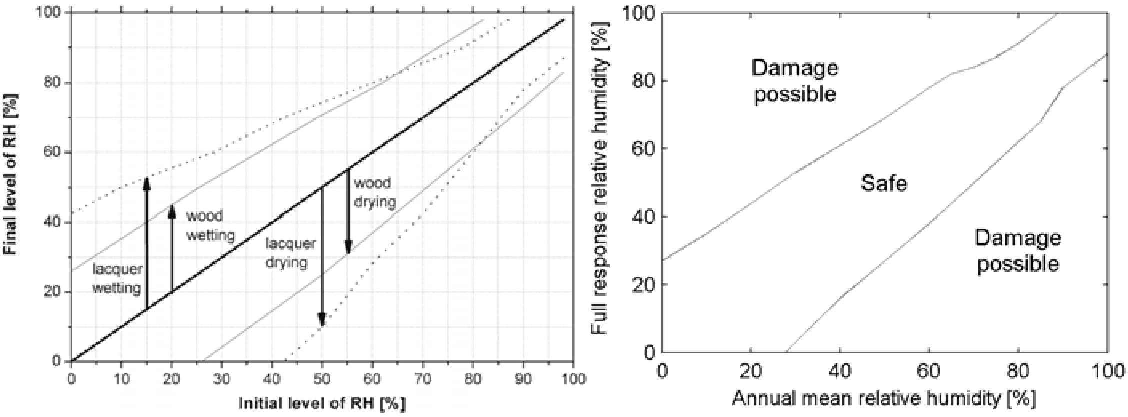


Figure 5.13: Assessing damage based on initial and final RH value [Bratasz et al., 2008], safe approach in which lacquer and wood remain elastic.

Wooden sculptures

For wooden sculptures Jakiela's graph (Chapter 3, figure 3.7) for sloped RH changes is used to assess gradients. The left graph of figure 5.14 shows this graph and states whether elastic or plastic behavior occurs. The right graph shows the verdict for the risk assessment.

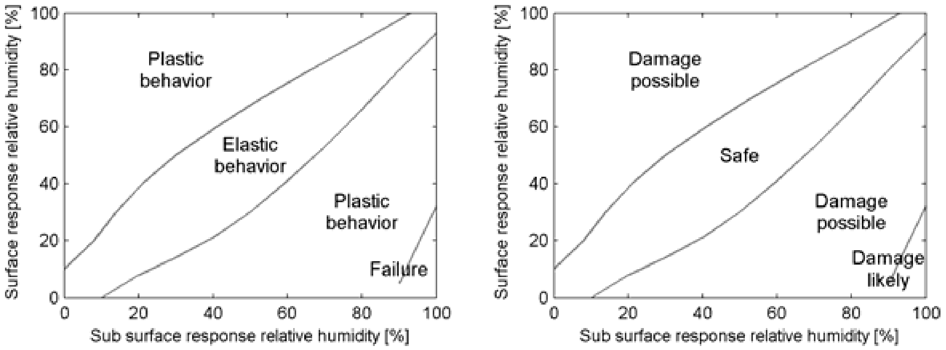


Figure 5.14: Mechanical behavior (left) and risks for mechanical damage (right) for a wooden sculpture.

5.2.5. Representation

Figure 5.15 shows the final result of the risk assessment method. The top part shows in text the results obtained from the analyses. The bottom part shows six graphs that correspond to the analysis methods of the objects. Table 5.3 shows the determination of risks for each degradation principle.

In 5.15, risks on mould growth are presented in text ('safe', 'germination?' or number of mm growth during the period assessed) and the top left graph shows data points relative to germination curves or – if germination takes place – to mycelium growth curves.

The LM is calculated for the entire period. This is displayed in the top middle graph. Averages are calculated and displayed as a number.

Risks to the base material are assessed for objects 2, 3 and 4. Relative humidity responses are compared to Mecklenburg, Bratasz and Jakiela respectively; results are displayed in the bottom graphs. Data in the elastic regions only result in 'safe', part of the data in plastic regions causes 'damage possible' and if data is in the failure region, 'damage likely' is to be expected.

Risks on damage for the pictorial layer are displayed in the top right graph. In case of a deviation from the average RH of more than 15%, 'damage possible' is displayed. If the amplitude of one or more fitted sine curves exceeds the 'gesso on 10 mm wood' curve in the graph the verdict is 'damage likely'.

Figure 5.16 is short for figure 5.15; risks are converted into colors. Not important degradation aspects (base material and pictorial layer damage to paper objects; pictorial layer damage to furniture and sculptures) remain white. LM below 0.75 is turned into red, in between 0.75 and 1 into orange and over 1 into green. This figure is used to compare risks in various rooms.

5.3. EXAMPLES

In this section results for one room in one museum are generated and discussed. Later on every room in one museum is assessed and compared. Results for all museums are discussed in chapter 6.

5.3.1. One room

Figure 5.15 presents the specific risk assessment method for Museum 5 Room 1. Paper objects are safe in this room, but their lifetime is not very long. Panel paintings are safe as far as mould growth and the base material are concerned. The RH change over time might damage the pictorial layer. For furniture and wooden sculptures the indoor climate is safe.

5.3.2. A museum

This paragraph contains results of Museum 5. Table 5.2 displays results in a tabular form, while figure 5.17 and 5.18 show risks for the average room conditions and conditions near surfaces respectively.

Table 5.2: Risk assessment method: results for Museum 5, Room 1.

Method 3: Risks	Paper		Panel painting				Furniture			Wooden sculpture		
Museum 5	Mould	LM	Mould	LM	Base	Pict	Mould	LM	Base	Mould	LM	Base
Room 1	Safe	0.893	Safe	1.02	Safe	MR	Safe	1.03	Safe	Safe	1.02	Safe
Room 2	Safe	1.25	Safe	1.10	MR	Safe	Safe	1.10	Safe	Safe	1.10	Safe
Room 3	Safe	1.35	Safe	1.18	MR	Safe	Safe	1.18	Safe	Safe	1.18	Safe
Room 4	MR	1.35	MR	1.11	MR	Safe	MR	1.11	Safe	MR	1.11	MR
Room 5	Safe	0.914	Safe	1.01	Safe	MR	Safe	1.01	Safe	Safe	1.01	Safe
Room 6	Safe	1.22	Safe	1.10	MR	Safe	Safe	1.10	Safe	Safe	1.10	Safe
Room 7	Safe	1.07	Safe	1.01	MR	MR	Safe	1.01	Safe	Safe	1.01	Safe
Room 8	MR	1.22	MR	1.10	MR	MR	MR	1.10	Safe	MR	1.11	MR

LM = Lifetime Multiplier; Base = Base material; Pict = Pictorial layer; HR = High Risk, MR = Moderate Risk

According to table 5.2 paper objects can best be placed in room 3. This room has the highest lifetime multiplier, while there is no risk on fungal growth. Room 4 shows the same LM, but here a minor risk for fungal growth occurs. Room 1 and 5 both show a shorter LM.
Panel paintings are not safe in this museum. Room 4 and 8 show a moderate risk on fungal growth. Mechanical damage to the base material occurs in rooms 2, 3, 4, 6, 7 and 8. Room 1 and 5 show moderate risks for damage to the pictorial layer.
Furniture and wooden statues also experience a moderate risk on fungal growth in room 4 and 8. Only in room 8 a moderate risk for damage to the base material of the wooden sculpture occurs.

Near surfaces a different indoor climate has been measured. In room 7 this local climate leads to more risk for mechanical damage to the base material of wooden sculptures. In room 5 panel paintings experience less risk on damage to the pictorial layer.

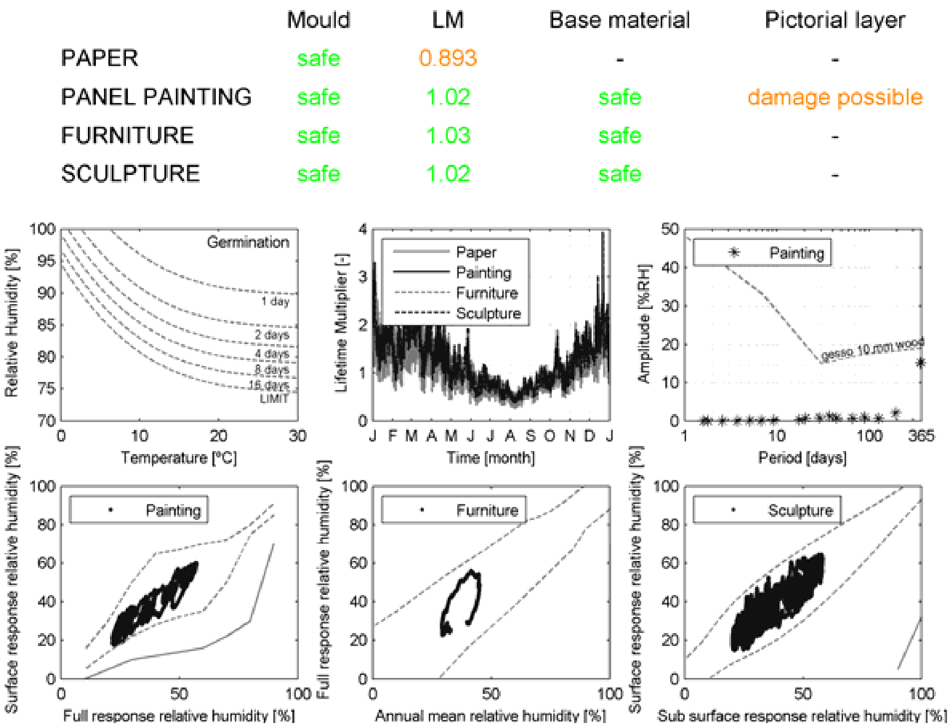
5.4. CONCLUSIONS

The specific risk assessment method introduced in this chapter calculates risks to four specific objects. The results are easy to interpret: colors indicate the amount of risk for each object. Moreover, this method uses all climatic data values: the influence of all temperature and relative humidity data on preservation quality of the indoor climate is assessed.

It is important that a whole year of climatic data – or multiple whole years – is used for the analysis. Otherwise calculated risks might not be representative for the actual risks.

The response time of the objects is important for the determination of climate experienced by the objects. This response time is influenced by the state of the object. Damaged surface layers will increase moisture transport, thus causing the response time to decrease. Therefore a damaged object becomes more sensitive to changes in RH than a similar undamaged object.

Only four objects are assessed. Although these four objects represent a large part of the collection found in museums, it would be useful to add more objects to this method.



	Mould	LM	Base material	Pictorial layer
PAPER	safe	0.893	-	-
PANEL PAINTING	safe	1.02	safe	damage possible
FURNITURE	safe	1.03	safe	-
SCULPTURE	safe	1.02	safe	-

Figure 5.15: Specific risk assessment method for Museum 5, Room 1.

Table 5.3: Determination of risks for each degradation principle.

	Small risk (green)	Medium risk (orange)	High risk (red)
Mould	SAFE Germination factor ≤ 0.2	GERMINATION? Germination factor > 0.2 & Mycelium growth = 0 mm	… MM GROWTH Mycelium growth > 0 mm
LM	LM > 1	0.75 < LM ≤ 1	LM ≤ 0.75
Base material	SAFE In elastic region	DAMAGE POSSILBE In plastic region	DAMAGE LIKELY In failure region
Pictorial layer	SAFE Difference between RH experienced and annual mean < 15%	DAMAGE POSSIBLE Difference between RH experienced and annual mean > 15%	DAMAGE LIKELY Amplitude and period of fitted sine function > than 'gesso on 10mm wood'

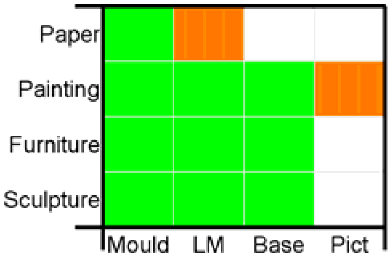
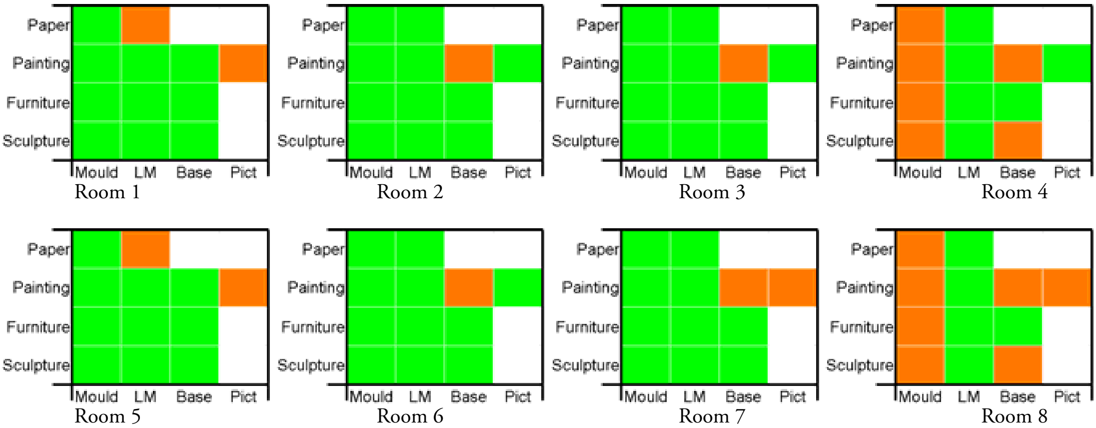


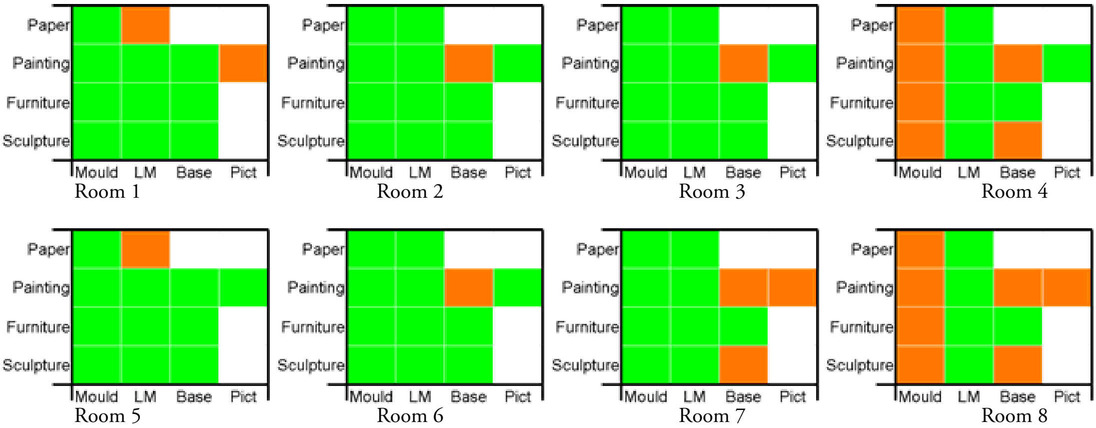
Figure 5.16: Risk overview for the specific risk assessment method for Museum 5, Room 1.



Room 1 Room 2 Room 3 Room 4

Room 5 Room 6 Room 7 Room 8

Figure 5.17: Specific risk assessment method for Museum 5, Room 1 to 8, indoor air conditions.



Room 1 Room 2 Room 3 Room 4

Room 5 Room 6 Room 7 Room 8

Figure 5.18: Specific risk assessment method for Museum 5, Room 1 to 8, surface conditions.

6

Specific risk analysis

In chapter 5 the specific climate risk assessment method is presented. In this chapter, that method is applied to the permanent measurement results as described in chapter 2: an overview of risks in the Dutch museums is given. Also the method is compared to the statistical operations and the general risk assessment method. An overview of museums with low risks only is provided.

Table B2 and C2 in Appendix B and C show the calculated specific risks for air conditions (table B2) and local surface conditions (table C2).

6.1. DATA ANALYSIS OF 20 DUTCH MUSEUMS

First the specific climate risk assessment method is applied to all measurements in museums. After that, results of the statistical operations are compared to the specific method. Additionally results of the general and specific method are combined and compared.

6.1.1. Specific climate risk assessment results

In figure 6.1 combinations of quality of envelope (QoE) and level of control (LoC) are shown. The total number of museums m and measured locations r are shown for each combination in the top left corner. Moreover, each combination shows risks to paper, panel paintings, furniture and wooden sculptures on mould growth, chemical degradation (Lifetime Multiplier) and mechanical damage (to the base material and the pictorial layer). The colors indicate the risk: green corresponds to low risk, orange to moderate risk and red to high risk.

The combination of QoE 1 and LoC 1 contains 41 positions in 4 museums. Of these 41 positions, fungal growth is expected on 2 positions, while the indoor climate is within the germination zone on 15 locations. Chemical degradation risk is low except for 1 position in which LM is moderate for paintings, furniture and sculptures. Mechanical damage is unlikely for furniture. A moderate risk on mechanical damage to the base material of wooden sculptures is encountered in 25 of the 41 positions, while for panel paintings 38 of 41 positions show moderate risks. For 10 locations also moderate risks for damage to the pictorial layer are noted.

Figure 6.1 also shows that risks on mechanical damage are small in LoC 3 and in QoE 3 & LoC 4. On some positions in QoE 1 & LoC 3 and in QoE 2 or 4 & LoC 4 conditions are within the germination area. All positions in QoE 4 & LoC 2 show moderate risk on damage to the pictorial layer of panel paintings. Furthermore, chemical degradation shows moderate risks in nearly all situations with a LoC higher than 1.

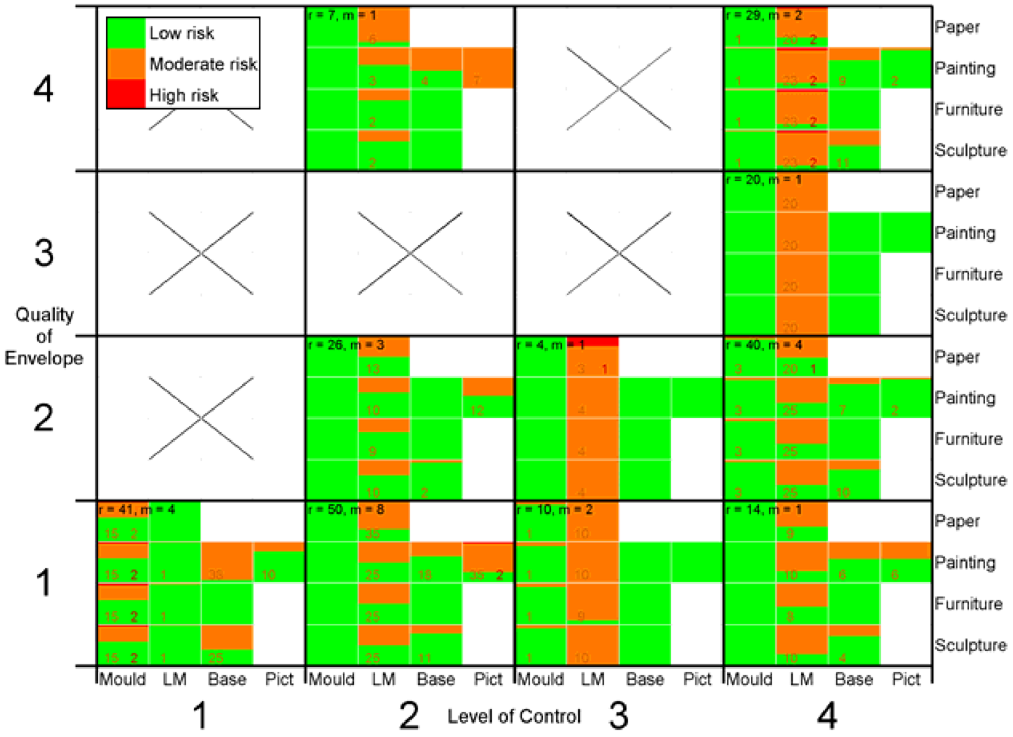


Figure 6.1: Specific climate risk assessment for combinations of QoE and LoC for exhibition rooms, storage areas and display cases.

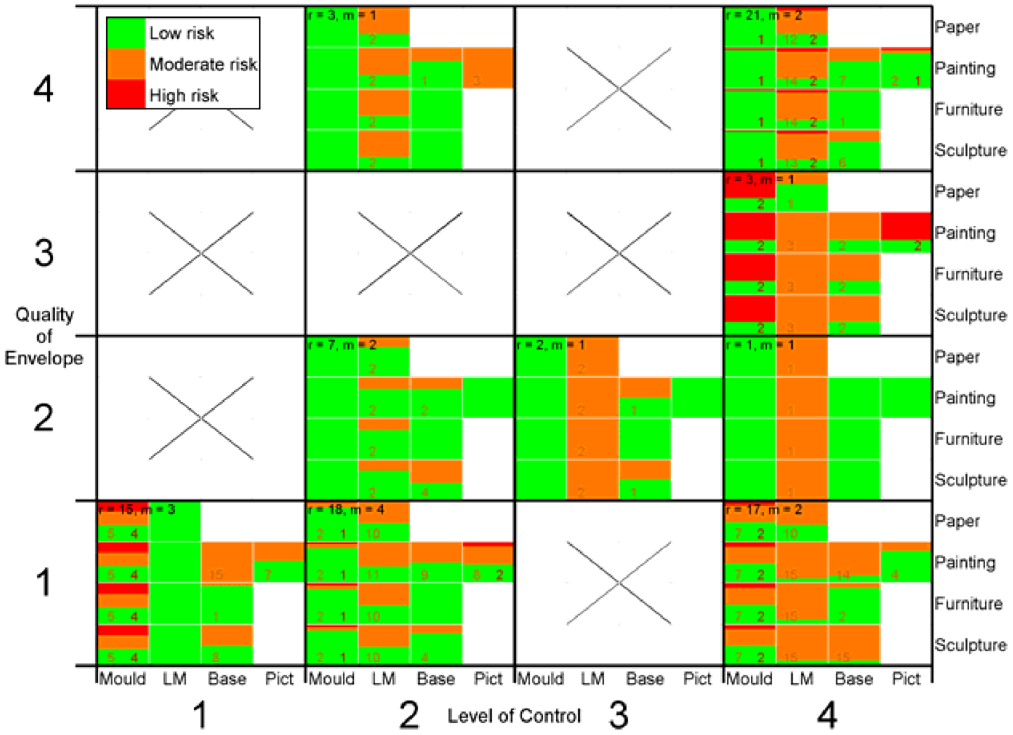


Figure 6.2: Specific climate risk assessment for combinations of QoE and LoC near surfaces.

High risks are only encountered for damage to the pictorial layer of panel paintings for 2 positions in QoE 1 & LoC 2. For mould growth, high risks are noted on 2 locations in QoE 1 & LoC 1, while chemical degradation shows high risks on 1 location in QoE 2 & LoC 3, 1 in QoE 2 & LoC 4 and 2 locations in QoE 4 & LoC 4.

Figure 6.2 shows the local conditions near building surfaces. LoC 1 and LoC 4 show high risks for mould growth on some locations. On average, it can be noted that near surfaces the risks increase.

6.1.2. Comparing statistical and specific method results

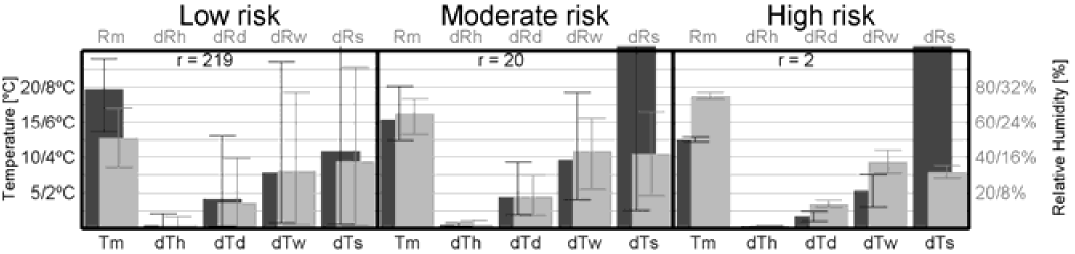


Figure 6.3: Statistical parameters for low, moderate and high risk on mould growth.

Figure 6.3 shows statistical parameters on temperature (dark grey) and relative humidity (light grey), sorted by low, moderate and high risk on fungal growth according to the specific climate risk assessment method. For each magnitude of risk mean T and RH values are shown (Tm and Rm), corresponding to the high numbers on the vertical axis. Also average hourly, daily and weekly changes are shown for temperature (dTh, dTd and dTw) and RH (dRh, dRd and dRw); these correspond to the lower numbers on the vertical axis. Moreover, also seasonal change is displayed for temperature (dTs) and RH (dRs), also corresponding to the lower numbers on the axis. The average value for all locations is displayed as a grey bar, while 2 horizontal lines connected with a vertical line show the spread in all locations. The number of locations is indicated by r.

Figure 6.3 shows that high risk on mould growth is encountered on locations where the average RH is higher than 70%. Additionally, also a high seasonal temperature change is recorded in case of high or moderate risks. This combination is logical because unheated buildings usually have a high average RH as well as a large seasonal temperature change. Shorter changes (hourly, daily or weekly) do not show a correlation between risk and magnitude of changes.

Figure 6.4 displays statistical parameters sorted by risk on chemical degradation. In case of low risks also the annual mean temperature is moderate: about 17°C average. Moderate and high risks show higher temperatures when compared to low risk, while for high risk also the average RH is higher when compared to moderate risk. Changes in temperature or RH show little correlation to chemical degradation risks; usually more stable conditions tend to have a higher average temperature than less stable conditions, resulting in a moderate to high risk. Locations with large seasonal differences also have a lower average temperature, resulting in low risk on chemical degradation.

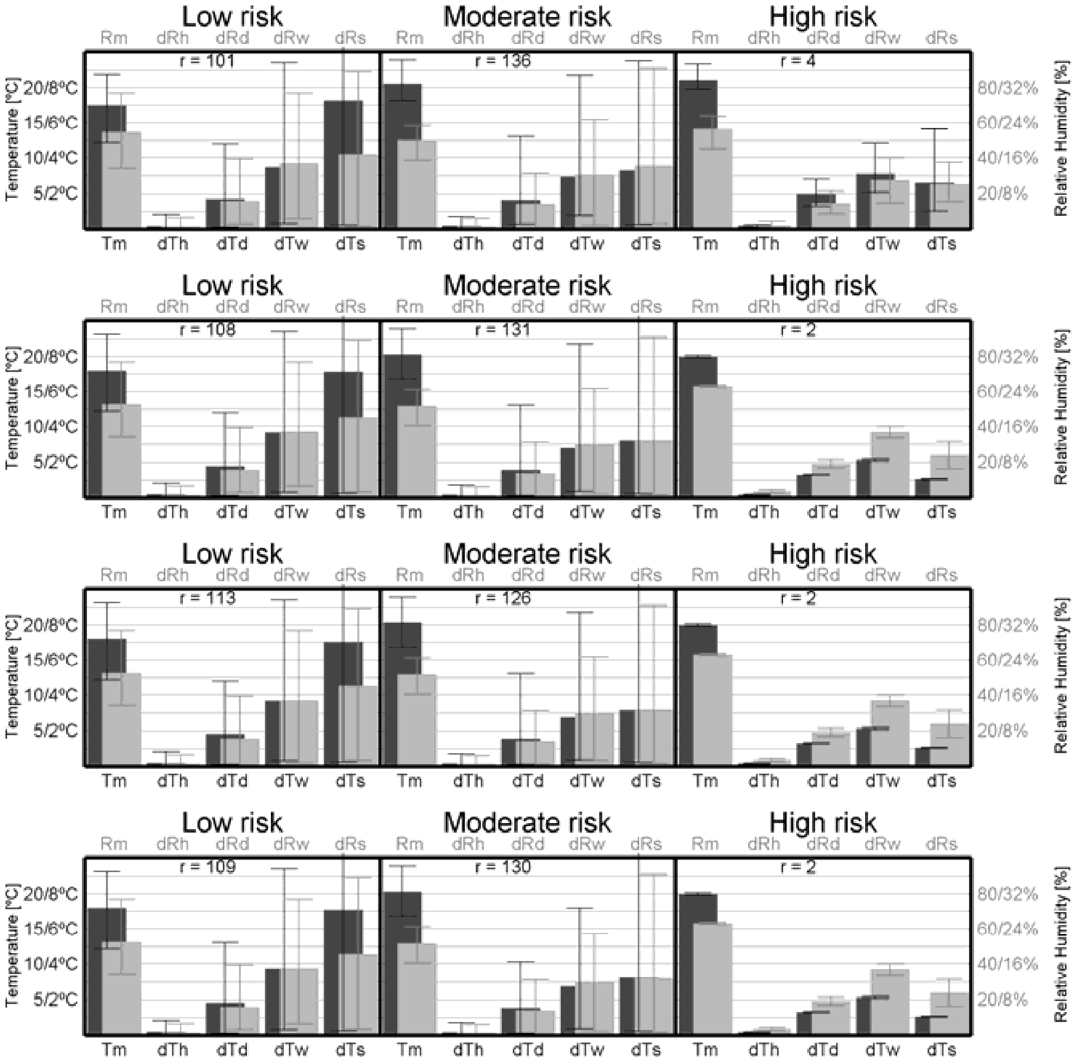


Figure 6.4: Statistical parameters for low, moderate and high risk on chemical degradation for paper (top graph), panel paintings (second graph), furniture (third graph) and wooden sculptures (bottom graph).

Figure 6.5 shows statistical parameters as a function of risk on mechanical degradation to the base material. For the panel painting (the top graph) the average temperature for low risk is 3°C higher than for moderate risk (20°C and 17°C respectively); the average RH is 8%RH lower. Seasonal and weekly temperature and RH changes are higher in case of moderate risk. The spread is, however, high, so it cannot be concluded that a low seasonal RH change always leads to a low risk for mechanical damage to the painting.

The middle graph shows results for furniture. Risks on mechanical degradation are low for all locations. This is caused by the long response time for furniture, combined with the relatively large area of elastic deformation. Furniture that is damaged will respond faster and more damage will occur earlier.

The bottom graph shows the relation between statistical parameters of the indoor climate and mechanical damage to the wooden sculpture. Locations that show a moderate risk tend to be slightly cooler and more humid than locations that show low risk. Also higher seasonal changes in both temperature and relative humidity are noted.

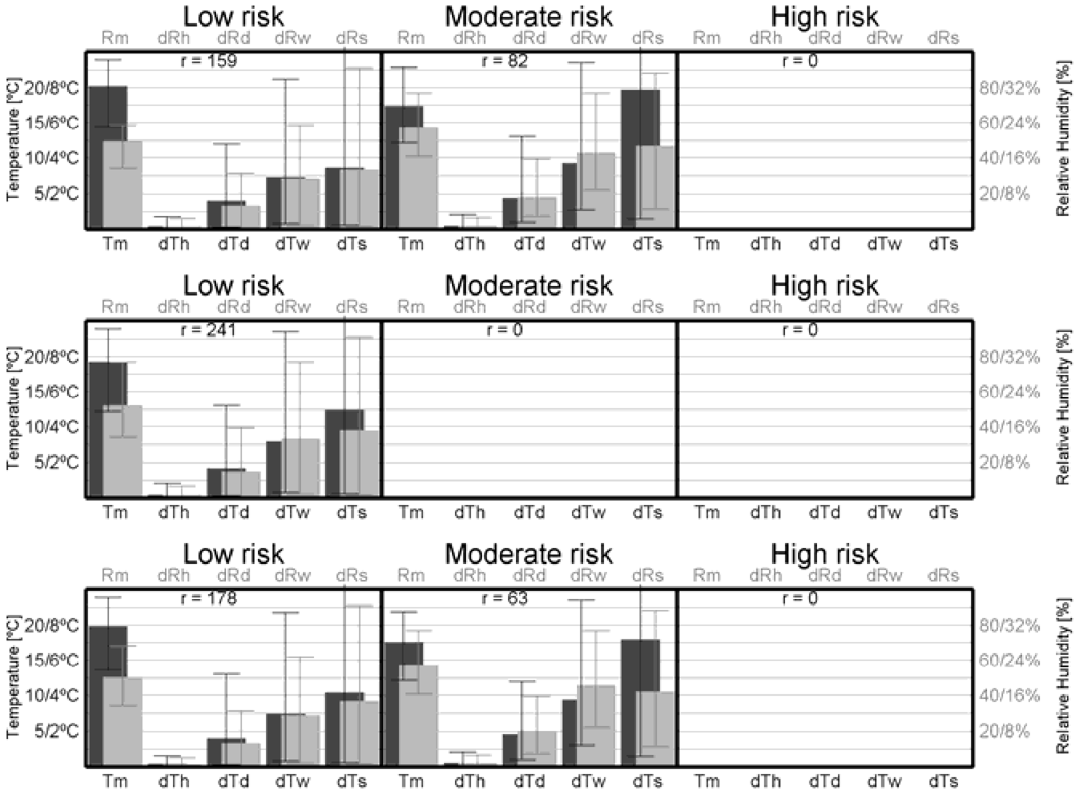


Figure 6.5: Statistical parameters for low, moderate and high risk on mechanical damage to the base material for panel paintings (top graph), furniture (middle graph) and wooden sculptures (bottom graph).

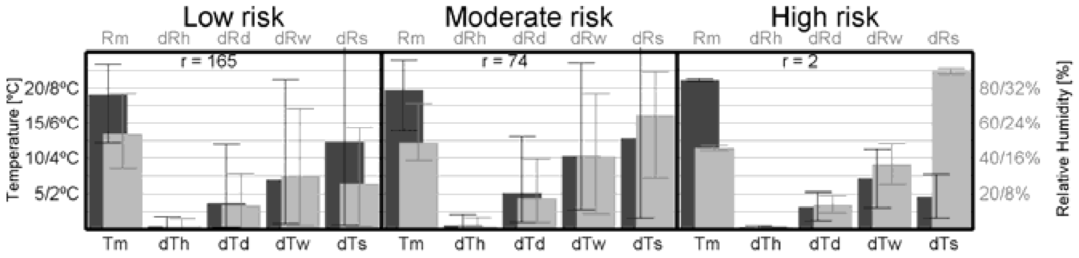


Figure 6.6: Statistical parameters for low, moderate and high risk on mechanical damage to the pictorial layer of the panel painting.

Figure 6.6 shows the relation between statistical parameters and risk on damage to the pictorial layer of panel paintings. As expected (see figure 5.12 in the previous chapter), high risk is noted for large seasonal changes in RH. Moderate risk shows increased seasonal and weekly changes in RH when compared to low risk.

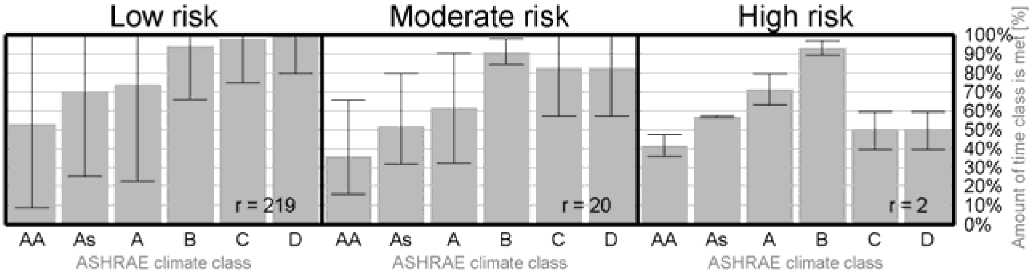


Figure 6.7: ASHRAE percentages for low, moderate and high risk on mould growth.

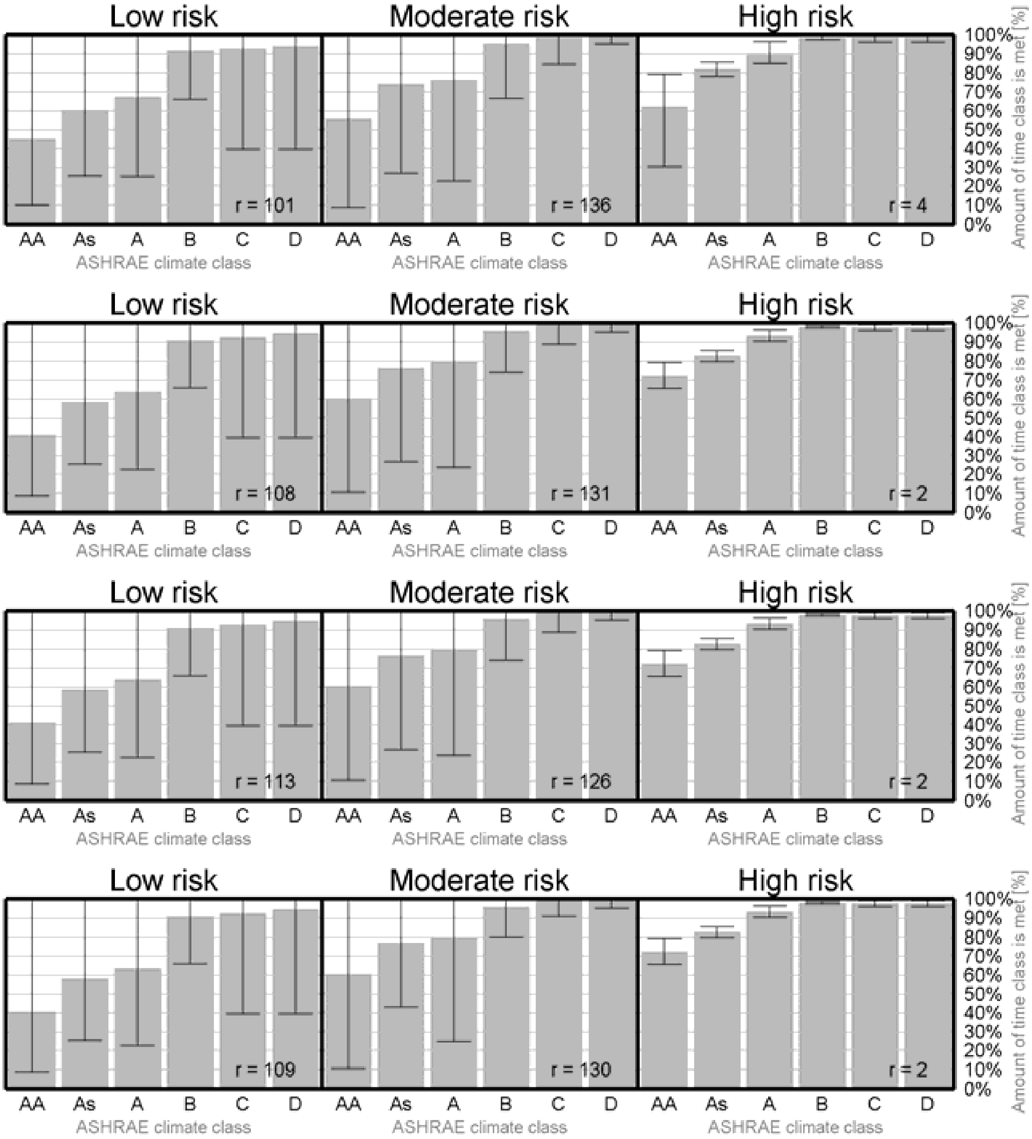


Figure 6.8: ASHRAE percentages for low, moderate and high risk on chemical degradation for paper (top graph), panel paintings (second graph), furniture (third graph) and wooden sculptures (bottom graph).

6.1.3. Comparing general and specific method results

Figure 6.7 shows for low, moderate and high risk on mould growth the corresponding scores on the ASHRAE climate classes. Classes C and D especially address risks on mould growth by limiting the maximum allowed RH to 75%RH. High risk on mould growth (on 2 locations) gives rise to a lower score on class C and D: in between 40 and 60% of time. Moderate risk on mould growth (20 locations) corresponds to in between 57 and 99% of time on class C and D. In case of low risk, percentages of 75% or higher on C and 80% or higher on D are noted. For the Dutch situation it is concluded that less than 80% of time in class D leads to a moderate to high risk on mould growth.

For low, moderate and high risks on chemical degradation, ASHRAE percentages are shown in figure 6.8. The link between the ASHRAE climate classes and chemical degradation is not very clear: for all objects a large spread in scores can be seen. The average values increase a little when going from low to moderate and to high risk. This can be explained by the fact that a more precisely controlled indoor climate, which usually obtains a higher ASHRAE score, has a higher temperature than 20°C and a higher relative humidity than 50%RH, leading to an LM lower than 1 (moderate risk) or even lower than 0.75 (high risk).

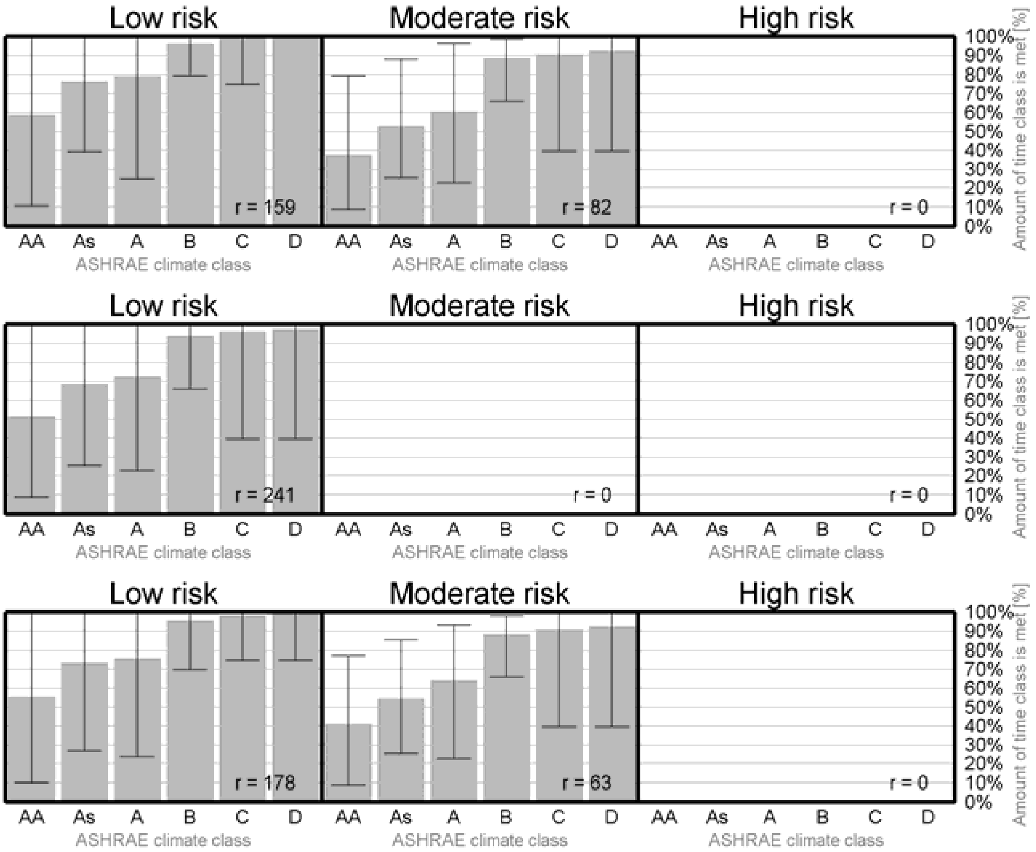


Figure 6.9: ASHRAE percentages for low, moderate and high risk on mechanical damage to the base material for panel paintings (top graph), furniture (middle graph) and wooden sculptures (bottom graph).

Figure 6.9 shows for low, moderate and high risks on mechanical damage to the base material the corresponding scores on the ASHRAE classes. For panel paintings it can be seen that for each ASHRAE class average, maximum and minimum scores decrease when going from low to moderate risk. Positions that obtained more than 80% score on AA, 88% on As, 97% on A or 99% on B all have low risk on mechanical damage to the base material of panel paintings.

Furniture is not harmed by any of the measured climates: all positions obtained a low risk on mechanical damage to furniture.

Mechanical damage to wooden sculptures is low for positions that score more than 73% on AA, more than 82% on As, more than 90% on A or more than 97% on B.

The percentages states above merely illustrate that the outliers determine whether damage occurs or does not occur. A 100% score on ASHRAE class B means that risk on mechanical damage to sculptures is low, while a 90% score on A might lead to a moderate risk.

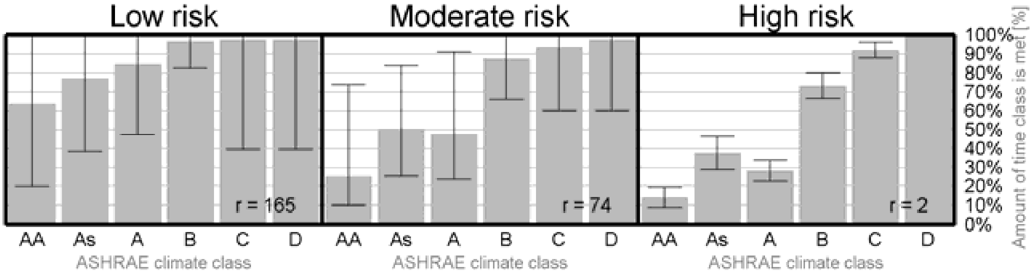


Figure 6.10: ASHRAE percentages for low, moderate and high risk on mechanical damage to the pictorial layer of the panel painting.

Figure 6.10 shows for low, moderate and high risk on damage to the pictorial layer of a panel painting the corresponding scores on the ASHRAE climate classes. Scores higher than 74% on AA, 83% on As and 91% on A lead to a low risk on damage to the pictorial layer.

When trying to combine the risks stated above, it cannot be concluded that a certain ASHRAE percentage for a class directly leads to a risk. The link between mechanical damage and ASHRAE percentages is clear, while for chemical degradation and mould growth the correlation is more complicated.

6.2. MUSEUMS WITH LOW RISKS ONLY

The combination of low risks for mould, chemical degradation and mechanical degradation can be found in 23 locations on a total of 241. Interestingly, these low risk locations are located in various types of buildings using various types of climate systems: figure 6.11 shows these locations.

The objects in the specific climate risk assessment are completely safe in 2 unheated rooms in monumental buildings, in 4 heated rooms in monumental buildings of which 2 have better glazing systems, 13 in full air conditioned rooms that are in a monumental building with improved glazing and also 4 in a new storage facility.

Quality of Envelope / Level of Control	1	2	3	4
4		0 of 7		4 of 29
3				0 of 20
2		2 of 26	0 of 4	13 of 40
1	2 of 41	2 of 50	0 of 10	0 of 14

Figure 6.11: Locations where all climate degradation risks are low.

6.3. CONCLUSIONS AND RECOMMENDATIONS

When assessing the risks on 241 locations in 20 Dutch museums, no high risks are found except for 2 locations where fungal growth is expected and 2 locations where mechanical damage to the pictorial layer of paintings is expected. These 4 locations are in QoE 1 buildings with LoC 1 and LoC 2 respectively.
Additionally, some locations experience high risks on chemical degradation, caused by a combination of high average temperature and high average RH. This occurred in QoE 2 and 4 in combination with LoC 3 and 4.

Moderate risks can be found almost anywhere. Most locations, 218 out of 241, show an increased risk for at least one of the degradation processes.

Of all 241 locations, 23 have low risks for all degradation principles and all objects. This is the result of a well balanced situation, in which building, climate system and local measures closely fit together.

The specific climate risk assessment method clearly shows which objects are at risk and by which degradation process. Of the four objects, furniture is not very critical since no mechanical damage is observed on any of the locations. It is important to note, however, that objects that are already damaged respond faster to changes in RH: cracked decorative of protective layers increase permeability and cause the object to come to an equilibrium with its environment much faster.

The correlation between the ASHRAE climate classes and risk on mechanical degradation is clear. A climate that is within ASHRAE class B for 100% of time does not lead to mechanical risk for any of the objects examined in the specific climate risk assessment. Although stricter classes lead to less risk (as mentioned in ASHRAE table 3.1 in this thesis), these risks are only valid when the stricter class is met a considerable amount of time. A 97% score on class A leads to a comparable risk as a 100% score on B.
The ASHRAE climate classes do not include chemical degradation; this type of degradation can be slow or fast regardless of the climate class achieved. Fungal growth is included, but rather in a crude way. The effect of temperature on fungal growth is not included; only RH is looked at and therefore the maximum allowed RH is lower than needed, especially in colder environments. The specific climate risk assessment method is therefore more sophisticated than the general climate risk assessment method.

7

Modeling indoor climates

In chapter 2 a matrix is introduced that combines quality of envelope (QoE) and level of control (LoC). The measurement data in chapter 4 were not sufficient to fill this matrix completely: some combinations of QoE and LoC could not be found among the Dutch museums. A model with varying QoE's and LoC's would allow filling the gaps, although it would be wise to try and find other museums that fill these gaps to check whether this extrapolation is valid. Moreover, such model can be used to predict the indoor climate when boundary conditions change. These boundary conditions may consist of construction, use in terms of visitor numbers, outdoor climate, climate systems or control strategy. The influence of all these parameters on the preservational quality of the indoor climate can easily be calculated and compared.

Another advantage of using a model is the ability to estimate energy use. A climate system with an assumed infinite capacity will create set point conditions regardless of the building type; in this case the energy use shows the difference between building types in effort to obtain set point conditions. Energy use is also researched by Artigas [2007]; he measured indoor climate and energy use in 5 museums in the USA. He concluded that energy costs increase exponentially when decreasing the variance (bandwidth in controlling the RH); tighter control leads to an increase in energy use. The results were corrected for museum size and outdoor climate. He also concluded that the mid seasons (spring and autumn) are the most demanding period for the climate systems; during the heating season the demand was lowest. Another important conclusion is that heating for visitor comfort causes less control over the RH. Disadvantages of Artigas' research are that museums are not similar in size, construction and use, although he corrected the results for these differences. In a computer model these boundary conditions can easily be kept similar.

Marx Ayres[1989] modeled 5 museums and calculated costs for running the climate systems. He concluded that in all museums a set point of 50%RH was less costly when compared to 40%RH and 60%RH, in the US climate. Changing the bandwidth from ±2%RH to ±5%RH or ±7%RH did not make a significant difference in energy use; the author does not give an explanation although this seems an unexpected result. He suggests that it is best to control the museum RH at a less expensive moderate level of RH and to use micro climates to improve preservation when other levels are required.

Balocco [2006] used a 3D simulation model (Computational Fluid Dynamics) to predict indoor climate conditions; air temperature and air velocity were predicted using this model. The goal was to determine the influence of the climate system and solar radiation on air currents to assess microclimates. Unfortunately relative humidity was not included in this model, which is a major flaw. Nevertheless, the author concludes that CFD is a promising tool when refurbishing a monument into a museum.

Padfield [2005, 2008] described a passive storage room, which is located in an office building. The office is supposed to be at 20°C year round, while the storage room is free floating in temperature (outdoor climate on one side, office climate on the other); the amount of ventilation is adjusted to keep the RH within the desired bandwidth. Simulations were used to determine the thickness of the insulation layer in the storage room façade and in the wall between storage and office. Padfield shows that passive climate control is possible in archives and storage areas where no human comfort is required. In museum exhibition rooms a passive approach is also possible, but only if current climate guidelines are discarded. Relatively simple measures can be used to create a climate with satisfactory preservation quality.

For this study HAMBASE [de Wit, 2006] has been used. HAMBASE is a simulation model for heat and vapor flows in a building and is developed at the TU/e from 1987 until now. With the model the indoor temperature, the indoor air humidity and energy use for heating and cooling of a multi-zone building can be simulated.

Over the past 25 years a lot of experience is gathered in developing and using HAMBASE. In his thesis, Schellen [2002] used WaVo – a previous version of HAMBASE – for determining temperature, relative humidity and heating capacity in churches with various heating systems. Also Neilen used HAMBASE for simulations [Neilen, 2006]; she concluded that it is a suitable tool to perform global, whole building simulations. When more detailed calculations are needed, e.g. air flows and stratification, she recommends other tools. Van Schijndel [2007a] used HAMBASE for his integrated building heat, air and moisture modeling and simulation, in which it is coupled to Simulink. This enables the coupling of models with different time constants: HVAC components and controllers (order of seconds) and building response (order of hours).

HAMbase was validated using the ASHRAE test [ASHRAE, 2001] with satisfactory results.

This chapter describes the input for the existing simulation model that allows studying all 16 combinations of quality of envelope (QoE) and level of control (LoC). The output of the model consists of temperature and relative humidity for a period of one year; it is used to study differences in risks for collections. Also energy use for the climate systems is included in the output.

A parameter sensitivity analysis allows identification of the magnitude of changes in the output by changing the input; it is performed for this specific model. Individual changes to the building are assessed.

After that a set point sensitivity analysis is performed. The assumption is that by changing set points, or making set points dependent on the outdoor climate, energy can be saved while maintaining the same quality of preservation.

7.1. BASIC MODEL INPUT

To be able to assess the influence of Quality of Envelope (QoE) and Level of Control (LoC), a typical exhibition room layout (see figure 7.1) is put in the simulation model. This layout is based on common museum exhibition room specifications as encountered in several of the researched museums; this room is located at a corner of a building. The room consists of a single zone, 10m long, 10m wide and with a height of 3.5m. The ceiling, floor, north and east wall are adiabatic, which means that the zone is connected to other zones, identical in behavior, that are not part of the simulation. The south and west wall are external walls and have a window of 5 m^2 each. In appendix D a full description of the input for the model is provided.

This single zone is put into the model 16 times; for each zone some parameters are changed according to QoE and LoC. These parameters are displayed in table 7.1 and 7.2. The construction of the building depends on QoE: walls, glazing and infiltration rate (caused by leakages in the envelope) all change when improving the thermal quality of the envelope. Set points depend on LoC. The available capacity for heating, cooling, humidification and dehumidification is set to an unrealistically high value to make sure set points are actually achieved; this is deliberately chosen to stress the influence on energy use and also to show what happens near cold surfaces.

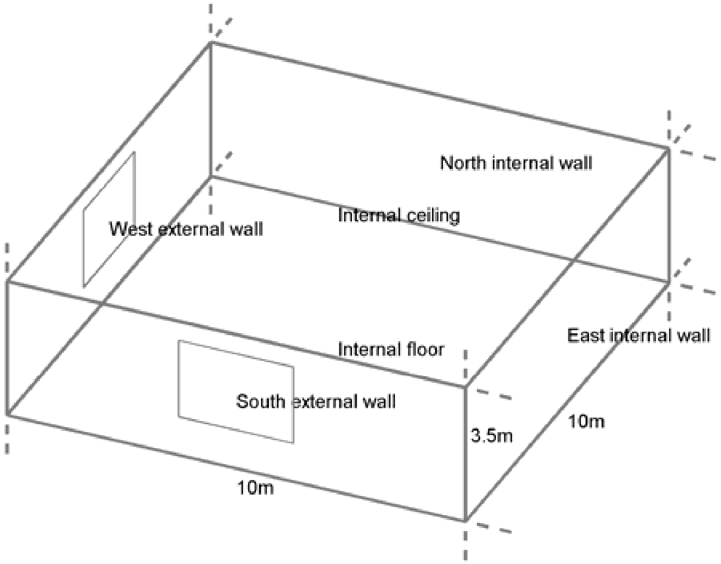


Figure 7.1: Input for the model: an exhibition room in a museum.

Table 7.1: Influence of QoE on input parameters.

	QoE 1	QoE 2	QoE 3	QoE 4
Exterior wall	Solid brick wall 400mm, plastered	Solid brick wall 400mm, plastered	Solid brick wall 400mm, insulation on the inside 100mm, plastered	Brick wall 100mm, cavity, insulation 150mm, brick 100mm, plastered
Glazing	Single	Double	Double low-e	Double low-e
Infiltration rate	1 h^{-1}	0.4 h^{-1}	0.2 h^{-1}	0.1 h^{-1}

Table 7.2: Influence of LoC on input parameters.

	LoC 1	LoC 2	LoC 3	LoC 4
Temperature set point [°C]	-	20°C (Heating)	20°C (Heating)	20°C (Heating), 22°C (Cooling)
Humidity set point [%]	-	-	40% (Humidification), 60% (Dehumidification)	48% (Humidification), 52% (Dehumidification)

The input of the model is a weather data file (of year 2005) measured in De Bilt by the Royal Netherlands Meteorological Institute (KNMI), see figure 7.2. It has an annual mean temperature of 10.7°C. Minimum and maximum were -14.0°C and 32.7°C, respectively. For RH, the minimum, average and maximum were 28%RH, 82%RH and 100%RH, respectively. The number of ice days (days with a maximum temperature equal to or below 0°C) was 5; 48 frost days (days with a minimum temperature equal to or below 0°C) were counted. Warm days (days with a maximum temperature equal to or over 20ºC), summer days (≥ 25ºC) and tropic days (≥ 30ºC) were 82, 29 and 3, respectively.

In the Netherlands, 2005 is regarded as a very warm and sunny year, with an average amount of precipitation (785 mm in total). The beginning of March was cold with 2 days of extensive snow (20 to 50 cm). As expected in future climate scenarios, the global (and therefore also the Dutch) climate will be warmer and more extreme, while precipitation will decrease in summer and increase in winter [Hurk et al., 2006]. The year 2005 matches this expectation, so it will be a good reference year for simulation. It is assumed that results will not change much over the next decade.

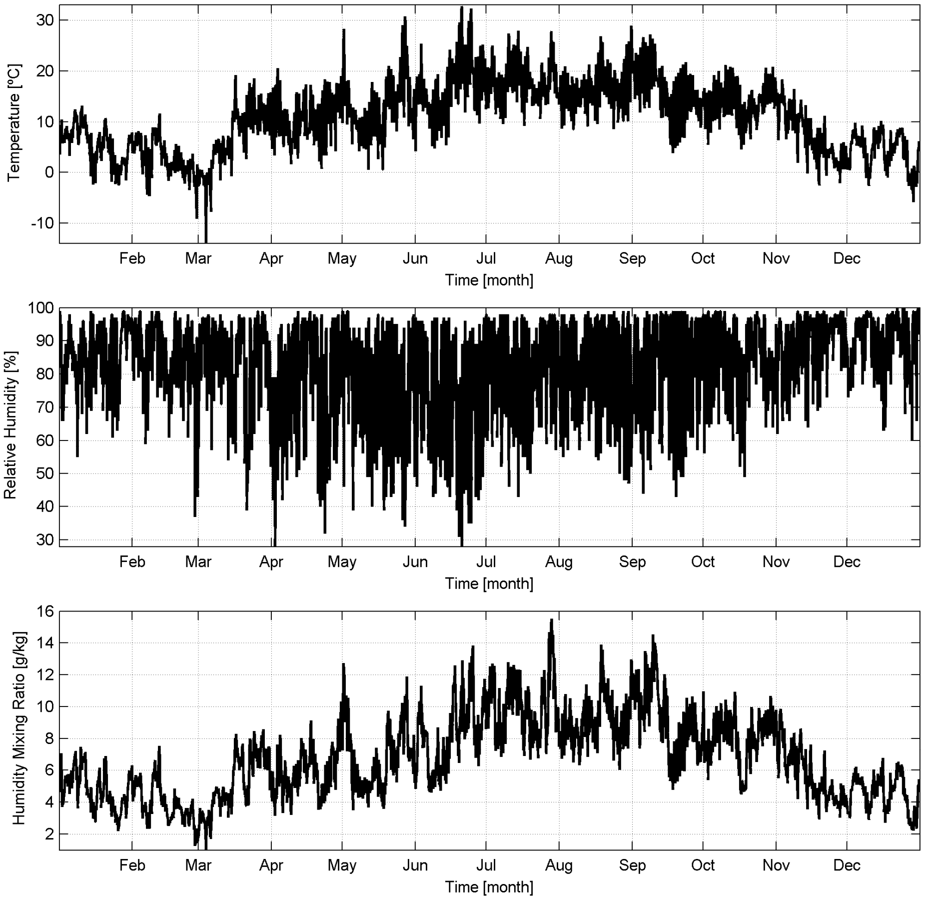


Figure 7.2: Climate used for simulation: De Bilt (NL), 2005 [KNMI].

7.2. Basic model results

Figure 7.4 shows T and RH in four zones: the corners in the matrix and therefore the extremes in indoor climate. The most primitive model, QoE 1 and LoC 1 (red), shows a cold, humid indoor climate. In winter, temperatures are low, sometimes just below 0ºC, but summer temperatures are quite tempered. RH ranges between 40 and 100%. When going from QoE 1 to QoE 4 (blue) temperatures are more constant and higher. Internal loads cannot be cooled, so summer temperatures rise to 30ºC. RH is more constant and ranges between 33 and 75%. Note that this is not a real situation; buildings with a modern envelope usually have a LoC of 3 or 4.

By going from QoE 1 and LoC 1 to a LoC of 4 (green), temperatures remain quite constant throughout the year. RH ranges from 25% in cold winter periods to 80% in summer, but the majority of RH values is in between 40 and 60%. The old and leaky envelope prevents the RH becoming more constant; only with a very high capacity a more stable RH might be achieved.

The combination of QoE 4 and LoC 4 (yellow) shows a constant climate, both in temperature and relative humidity. Set point values are achieved during the entire period.

Figure 7.3 contains data on temperature and humidity; the graph is explained in paragraph 4.1.1. In black, temperature data is displayed; RH data is displayed in light grey.

Changing LoC 1 to LoC 4 will diminish seasonal changes. Hourly changes are small in all combinations, but daily and weekly changes also decrease when improving the LoC.

Improving the QoE from 1 to 4 results in decreasing daily and weekly changes. Seasonal changes in temperature, however, increase. Well insulated buildings tend to overheat in summer – see also the blue line in figure 7.4 – due to internal heat production (people and lighting) and solar radiation, while cooling by infiltration is less.

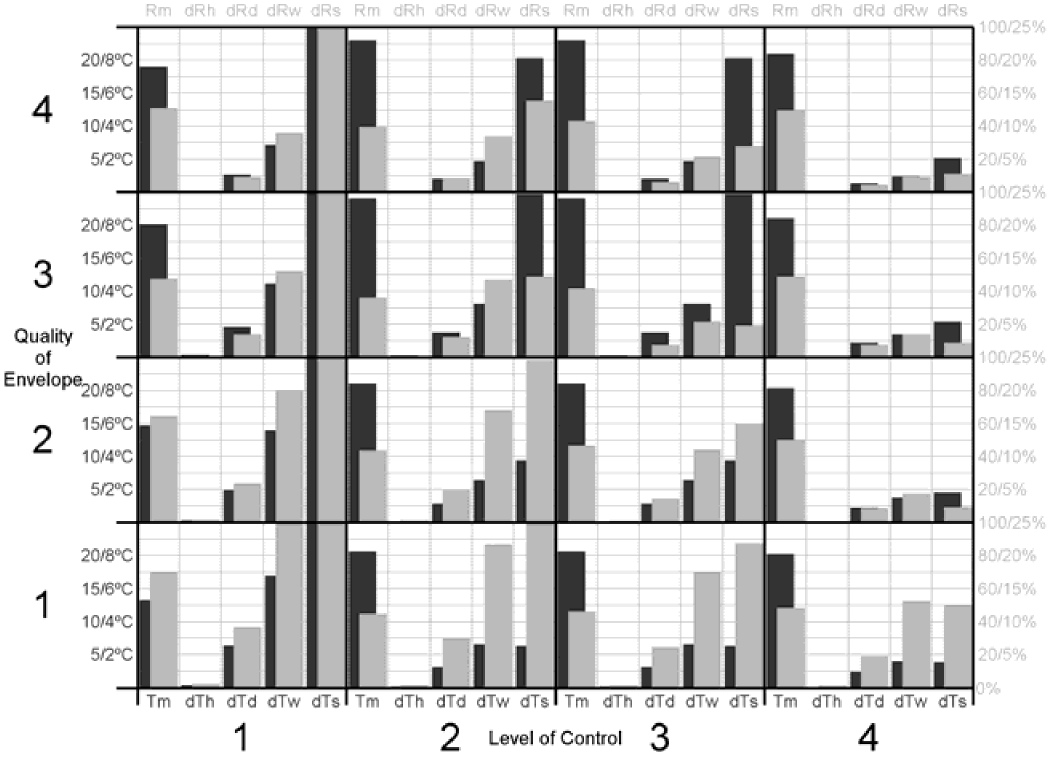


Figure 7.3: Statistical operations for T and RH matrix for all combinations of QoE and LoC.

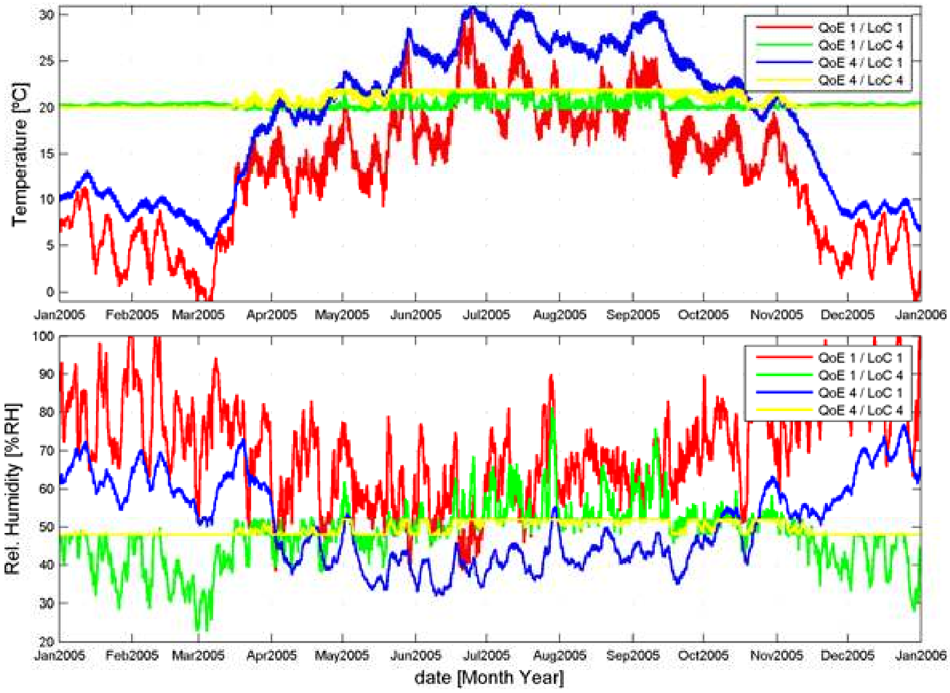


Figure 7.4: Simulated temperature and relative humidity in 4 of the 16 zones for year 2005.

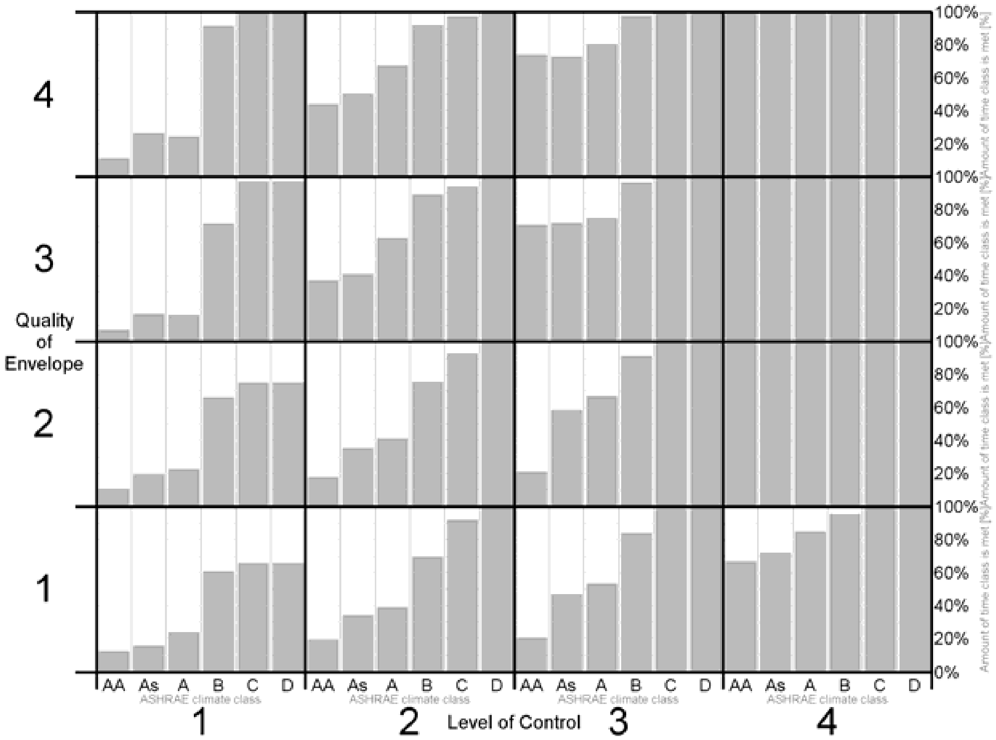


Figure 7.5: General climate risk assessment out of simulated data for all combinations of QoE and LoC.

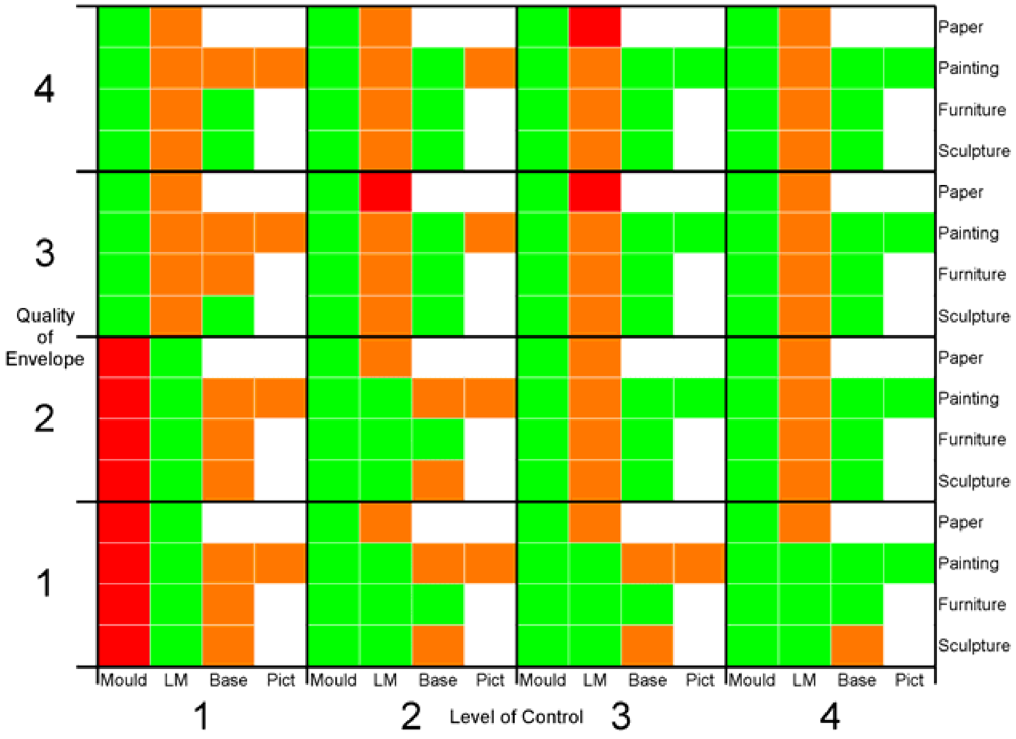


Figure 7.6: Specific climate risk assessment out of simulated data for all combinations of QoE and LoC.

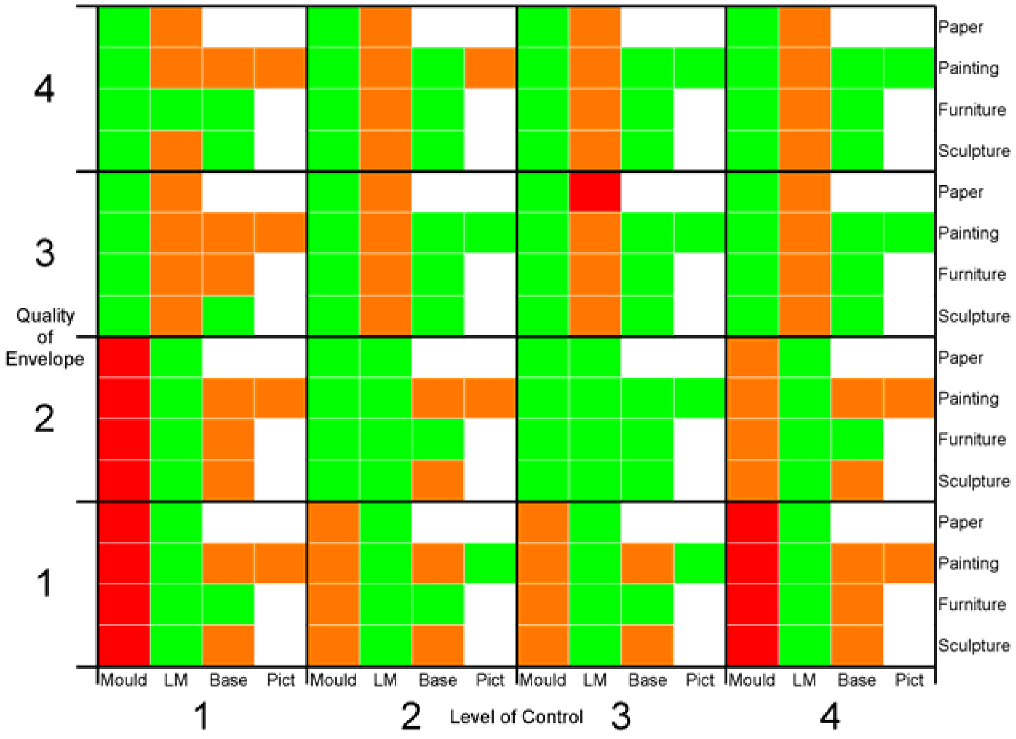


Figure 7.7: Specific climate risk assessment out of simulated data near surfaces.

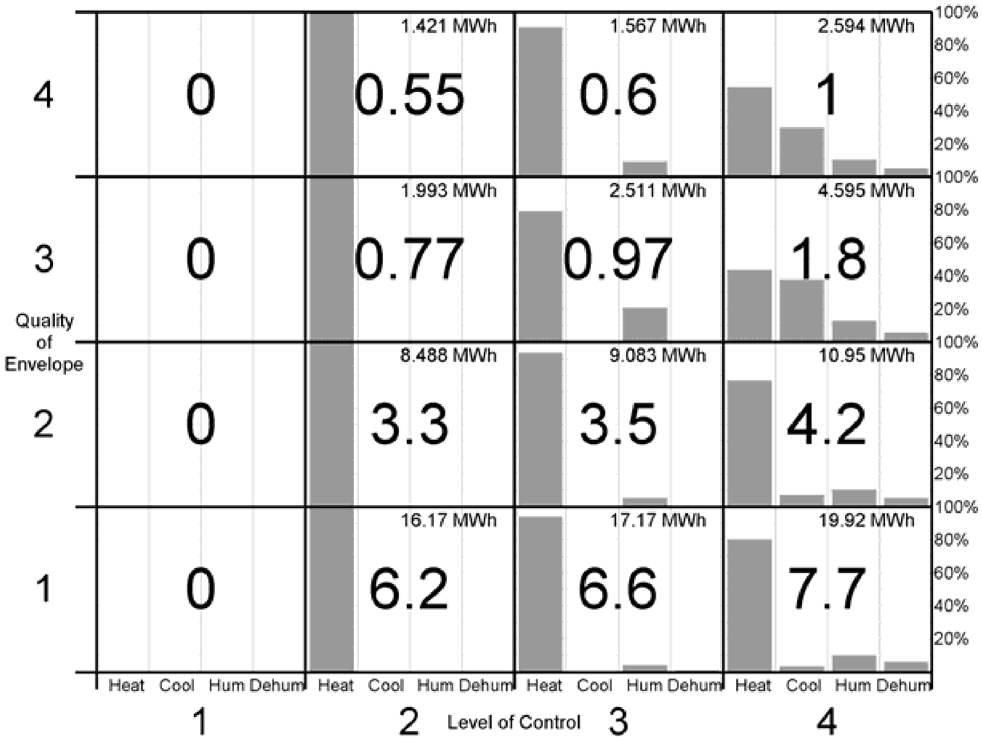


Figure 7.8: Energy use out of simulated data for all combinations of QoE and LoC.

Figure 7.5 displays the percentage of time the climate in each combination of QoE and LoC fits into an ASHRAE climate class. It shows that in LoC 4 and QoE 2, 3 and 4 theoretically all climate classes provided by ASHRAE are met during the entire reference year. Improving the LoC seems to be a better option than improving QoE: the ASHRAE scores increase considerably when going from left to right in the diagram, while going from bottom to top this increase is less obvious. This is also what is expected: improving the building will not automatically lead to a suitable climate, while controlling the climate according to a well defined set point with over dimensioned systems will. The most controlled climate (AA) can be maintained for QoE 2, 3 and 4 as long as the LoC is 4 (full air conditioning), which is to be expected on room level. It should be noted however that locally, especially near uninsulated surfaces, different T and RH values occur. Obviously, as will be explained further on, high control of the indoor climate in low quality envelopes will require large amounts of energy.

Figure 7.6 displays an overview of the risks for different types of collection for each combination of QoE and LoC using the specific climate risk assessment method. The objects do not experience the air temperature alone: they are also influenced by radiation of surfaces. In order to assess the climate the object experiences, the so-called operative temperature is assessed. This temperature consists for 60% of the air temperature and for 40% of the main radiant temperature of all surfaces (external and internal surfaces).

In QoE 1 and 2 in combination with LoC 1, risk on fungal growth on objects is high. When going from QoE 1 to 4, the LM decreases. Especially for paper objects, for which the LM is the most important aspect in preservation, this might be a problem. Also some of the risks on gradient damage or structural damage decrease, which is positive for preservation.

Improving the LoC also leads to less damage because of gradients or structural changes. In some cases – when heating is added – the LM diminishes.
All objects are safe in LoC 3 and 4 in combination with QoE 2, 3 and 4, except for paper objects (because of the LM).

Figure 7.7 shows the degradation risks near the building envelope. Instead of the operative temperature, now the conditions calculated near the envelope are used for the analysis. When starting at a QoE of 1 and LoC 1, improving the system to a LoC of 2 or 3 minimizes risks. LoC 4 on the other hand increases risks again to about the same level as in LoC 1. Tight RH control is not an option in a building that is thermally not improved, even if the systems are capable of actually reaching the set points: objects near the envelope are not very safe; they are only safe in the middle of the room. As presented in paragraph 4.2 and 6.1.1, local conditions can be risky to objects.

Figure 7.8 shows the normalized energy use for the different combinations. The bars indicate the percentage of energy use by the different components (heating, cooling, humidification and dehumidification). The total amount is displayed at the top of each square.
By changing the QoE from 1 to 2, the energy saved is about 45%, independent of the climate system used. Further improvements to a QoE of 3 save another 58 to 78%; savings are highest when the LoC is 2 (but overheating is more likely). QoE 4 reduced the energy used even further: 30 to 45% is saved when compared to QoE 3.
When comparing the best and the worst situation of LoC 4 in terms of energy use, the most efficient situation consumes only 13%. In LoC 1 no energy is used by climate systems; it limits however the usability of the museum by lack of thermal comfort during winter and delicate objects cannot be displayed there.

7.3. PARAMETER SENSITIVITY ANALYSIS

The basic model is tested for stability and sensitivity. This is done by changing the input parameters one by one: parameters are increased and decreased. Table 7.3 shows the correlation between energy use, average value and fluctuations in T and RH, for each of the input parameters. The individual results of all models are displayed in appendix D. When a positive correlation is found, a '+' is used. Negative correlations are marked '–'. When no clear difference is found, a '0' is put in the table.

Table 7.3: Influence of changes to indoor climate and energy use (out of simulation).

Measure	Tmean	ΔTshort	ΔTlong	RHmean	ΔRHshort	ΔRHlong	Eheating	Ecooling	Ehum	Edehum
Wall thickness	+	–	–	–	+	0	–	+	+	+
Exterior wall surface area	–	–	–	+	0	+	+	+	+	+
Glazing surface area	+	+	+	+	+	+	+	+	+	0
Interior wall surface area	+	–	–	–	–	0	+	+	+	+
Infiltration rate	–	–	–	+	+	+	+	0	+	+
Sun blinds	–	–	–	+	+	–	+	0	–	+
Visitors	+	+	+	–	+	–	–	+	+	–

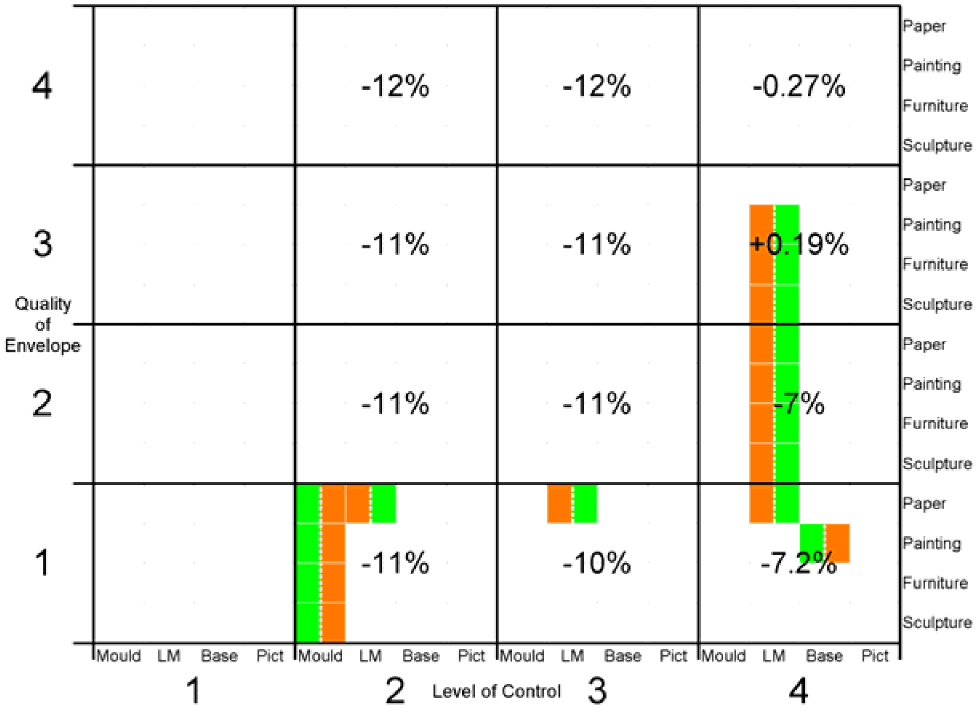


Figure 7.9: Comparison of risks and energy use, original (left) and after decreasing set point by 1 °C (variant A) (right); only differences are displayed. Low risks are colored green, moderate risks orange and high risks red.

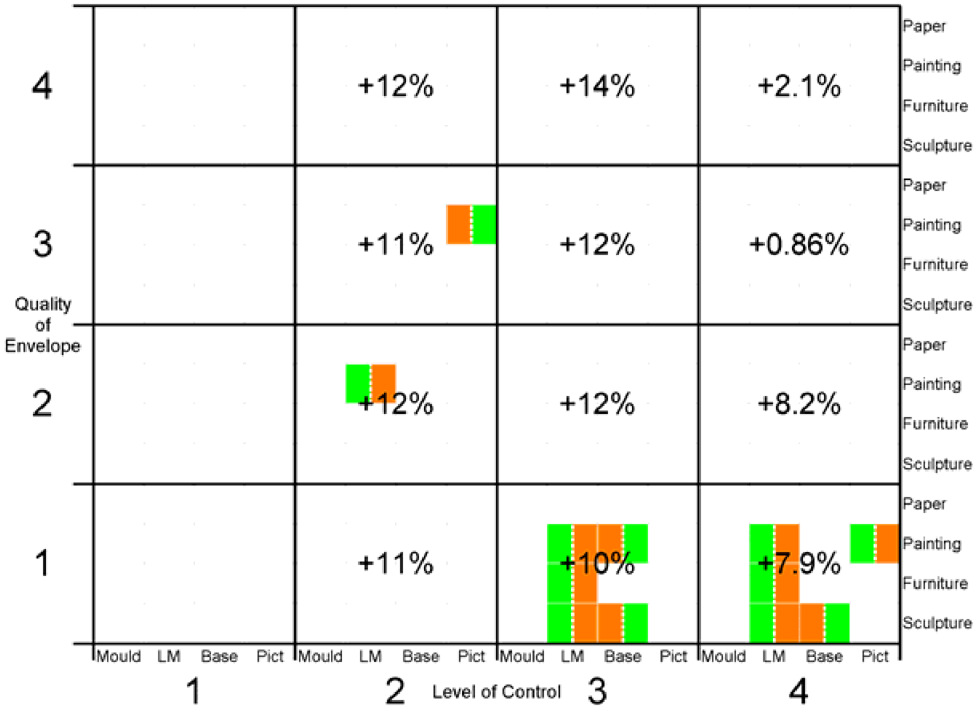


Figure 7.10: Comparison of risks and energy use, original (left) and after increasing set points by 1 °C (variant B) (right); only differences are displayed. Low risks are colored green, moderate risks orange and high risks red.

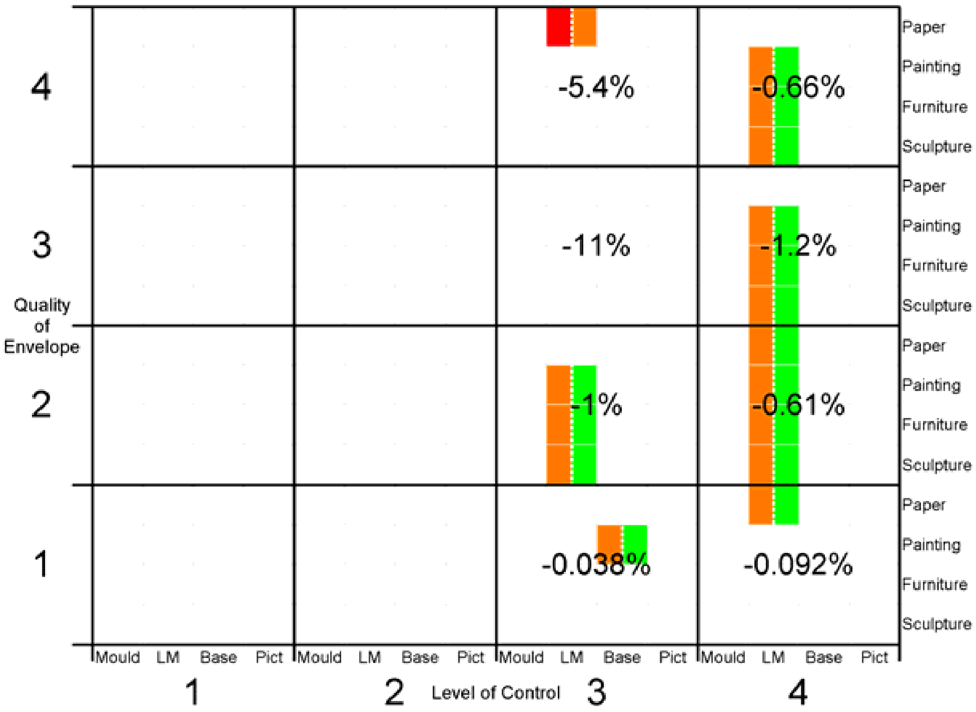


Figure 7.11: Comparison of risks and energy use, original (left) and after decreasing set point by 5% (variant C) (right); only differences are displayed. Low risks are colored green, moderate risks orange and high risks red.

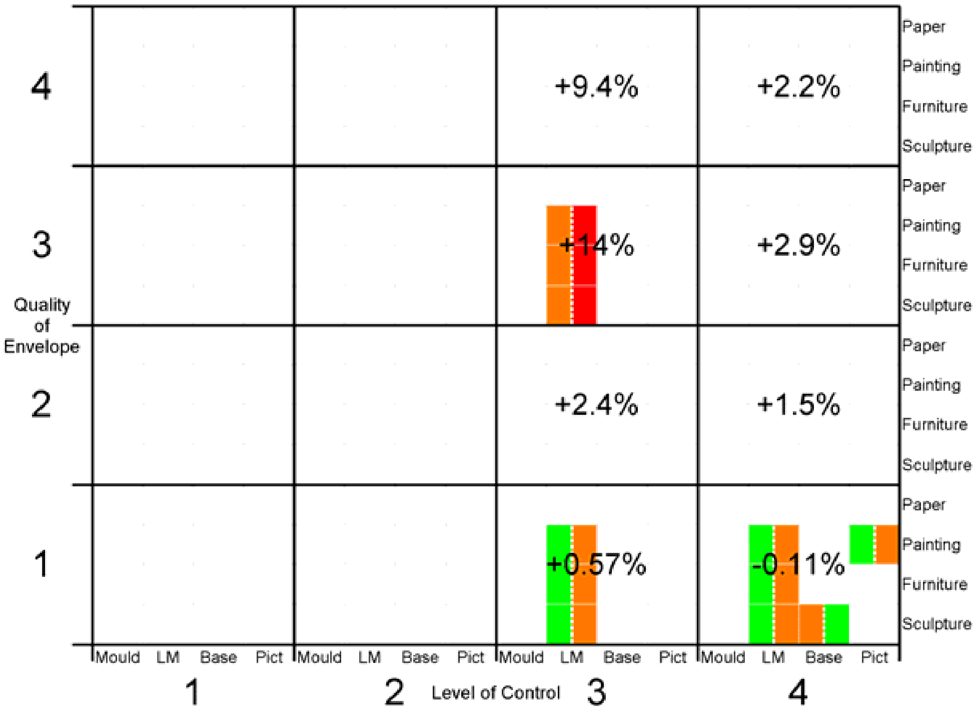


Figure 7.12: Comparison of risks and energy use, original (left) and after increasing set point by 5% (variant D) (right); only differences are displayed. Low risks are colored green, moderate risks orange and high risks red.

For preservation prediction especially changes in longer RH fluctuations are important. Table 7.3 shows that these fluctuations can be minimized by reducing the surface area of exterior walls, by reducing the glazing surface area and by reducing ventilation rate. Also increasing the amount of sun blinds or the number of visitors helps in minimizing these fluctuations. Especially the latter seems odd, but visitors tend to humidify the indoor air during the winter situation, while not changing the summer RH much. This leads to less fluctuation between the seasons.

Also mean temperature and mean RH contribute to some of the risks. When the results displayed in table 7.3 are assessed, the following remarks can be made. An increase in exterior wall thickness and/or interior wall surface area causes a higher mean temperature and a lower mean RH. Increasing the amount of visitors has the same effect. The opposite is expected from sun blinds, infiltration rate and exterior surface area: an increase in one of these factors leads to a decrease in mean temperature and an increase in mean RH. Increasing the glazing surface area leads to higher mean values for both temperature and RH.

7.4. INFLUENCE OF SET POINTS

Next to variations of the building envelope and climate system, set points also largely influence the indoor climate. Moreover, set points that are not chosen in relation to the envelope and local weather conditions have proven to lead to various problems, such as rotting of wooden beams and high energy consumption. The question is whether the choice for a certain set point has an effect on the degradation risks for objects. Table 7.4 provides an overview of all variants. Results of individual simulations can be found in appendix E. This part only focuses on differences in results between the basic case and the case discussed.

Table 7.4: Changes made to the set points in each simulated model.

Variant	Description	Paragraph
A	T set point - 1°C	7.4.1.
B	T set point + 1°C	7.4.1.
C	RH set point - 5%	7.4.2.
D	RH set point + 5%	7.4.2.
E	Set point T based on sine curve (T +/- 2°C)	7.4.3.
F	Set point RH based on sine curve (RH +/- 10%)	7.4.4.
G	Set point T and RH based on sine curves (T +/- 2°C, RH +/- 10%)	7.4.5.
H	Set point T based on outdoor temperature	7.4.6.
I	Set point T based on outdoor temperature, Set point RH based on sine curve (RH +/- 10%)	7.4.7.

7.4.1. Fixed temperature set point

In the basic case, a temperature set point of 20°C is used for heating in cold seasons and 22°C for cooling during hot seasons. Now, a simulation is performed with these set points decreased by 1°C (19 and 21°C, variant A) and another with increased set points (21 and 23°C, variant B). Figure 7.9 and 7.10 show a comparison between the basic case and the simulated results; only changed risks are shown (divided into a left and a right part, each individual square shows the original and the new risk) to simplify the comparison of the simulation. Also the change in energy use is displayed as a percentage.

Lowering temperature set point by 1°C increases the lifetime multiplier notably for paper objects in QoE 1 and for most objects in LoC 4 & QoE 1, 2 and 3. Risk on fungal growth increases in QoE 1 & LoC 2. Also the risk on damage to the base material of the panel painting in QoE 1 & LoC 4 increases.

By raising temperature set point, the LM decreases especially for QoE 1 and LoC 3 and 4. Panel paintings in QoE 3 & LoC 2 show a decrease in risk on damage to the pictorial layer while this risk increases for QoE 1 & LoC 4.

Slightly lowering temperature is a good idea in most cases; few risks increase and LM improves. Energy savings up to 12% can be reached. Only in airtight buildings in which cooling is installed lowering the set point during summer is not a good idea when looking at the energy use: the cooling capacity needed increases as does the total energy consumption.

Slightly raising temperature is not such a good idea; the LM decreases especially in buildings with a low QoE. Also energy use increases 0.9% up to 14%.

7.4.2. Fixed relative humidity set point

Alternatively temperature set points are kept the same and set points for relative humidity are changed. In the basic simulation, LoC 3 uses set points of 40% and 60% for humidification and dehumidification respectively, while LoC 4 uses 48% and 52%. These set points are decreased (variant C) and increased (variant D) by 5%. Results are displayed in figure 7.11 and 7.12, respectively.

In LoC 3 and 4 a decrease of 5% in the RH set point shows an improvement of the LM and also panel paintings in QoE 1 & LoC 3 are less likely to experience damage to the base material. Other risks do not change significantly, but energy consumption is reduced especially in QoE 3 and 4 in combination with LoC 3. Differences in energy saving are 0.04% up to 11% of the total energy needed by the climate system. Especially in LoC 3 / QoE 3 lowering the RH by 5% seems attractive.

Increasing RH set point shows a decrease of the LM, especially in QoE 1 & LoC 3 and 4 and in QoE 3 & LoC 3. Also the risk on structural damage to wooden sculptures decreases in QoE 1 & LoC 4 but risk on damage to the pictorial layer of the painting increases. Energy use increases except in QoE 1 & LoC 4; in this case the summer cooling and the leaky envelope make sure less dehumidification is needed in summer.

7.4.3. Seasonal change in temperature set point

Instead of a fixed set point (as in cases A up to D), a slowly changing set point is investigated in variant E to study the effects on energy use and preservation risks. The annual mean temperature is not affected, but in winter the set point is 2°C lower, while during summer a 2°C higher set point is applied. Please note that even the strictest ASHRAE climate class (class AA) allows a seasonal change in temperature of 5°C. The seasonal adjustment in set point is based on a sine curve; this is shown in figure 7.17.

In figure 7.13 results of implication of these set points are displayed. A comparison is made with the basic simulation.

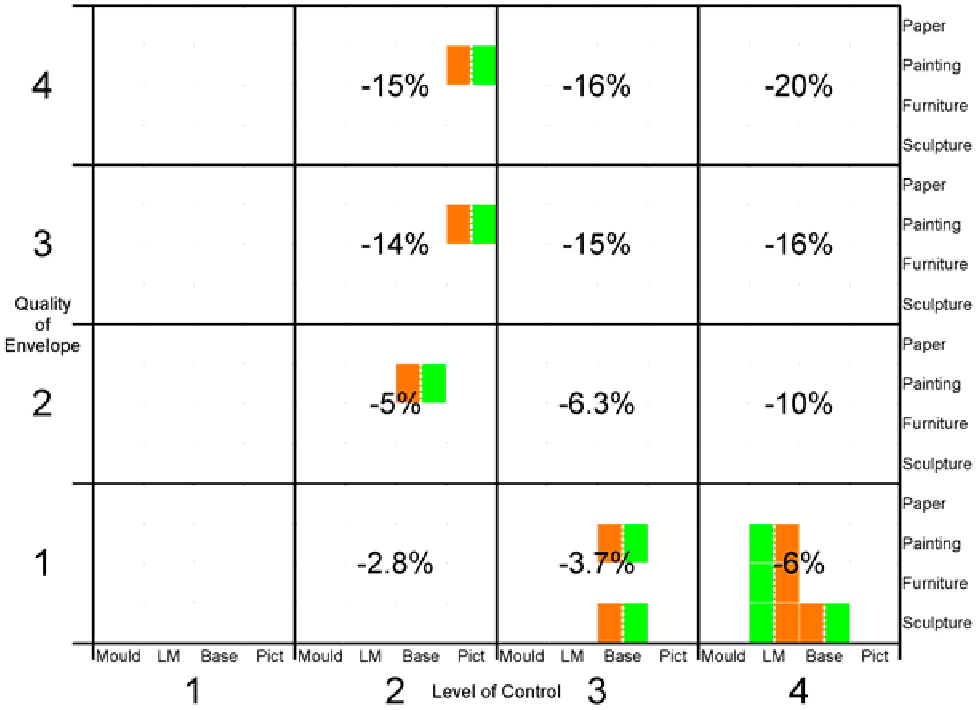


Figure 7.13: Comparison of risks and energy use, original (left) and variant E (right); only differences are displayed. Low risks are colored green, moderate risks orange and high risks red.

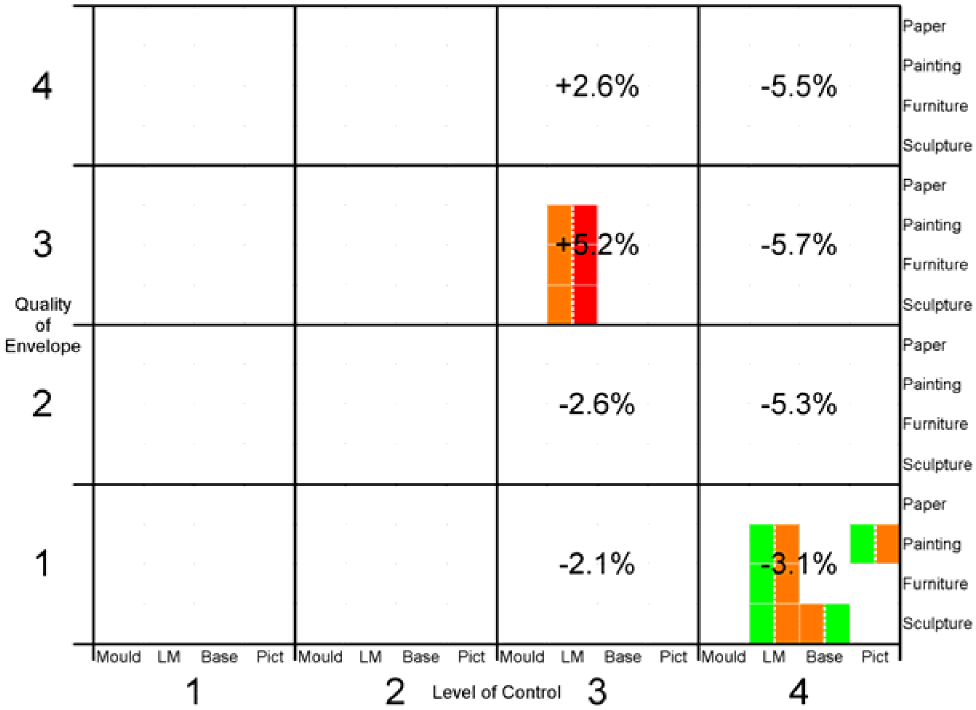


Figure 7.14: Comparison of risks and energy use, original (left) and variant F (right); only differences are displayed. Low risks are colored green, moderate risks orange and high risks red.

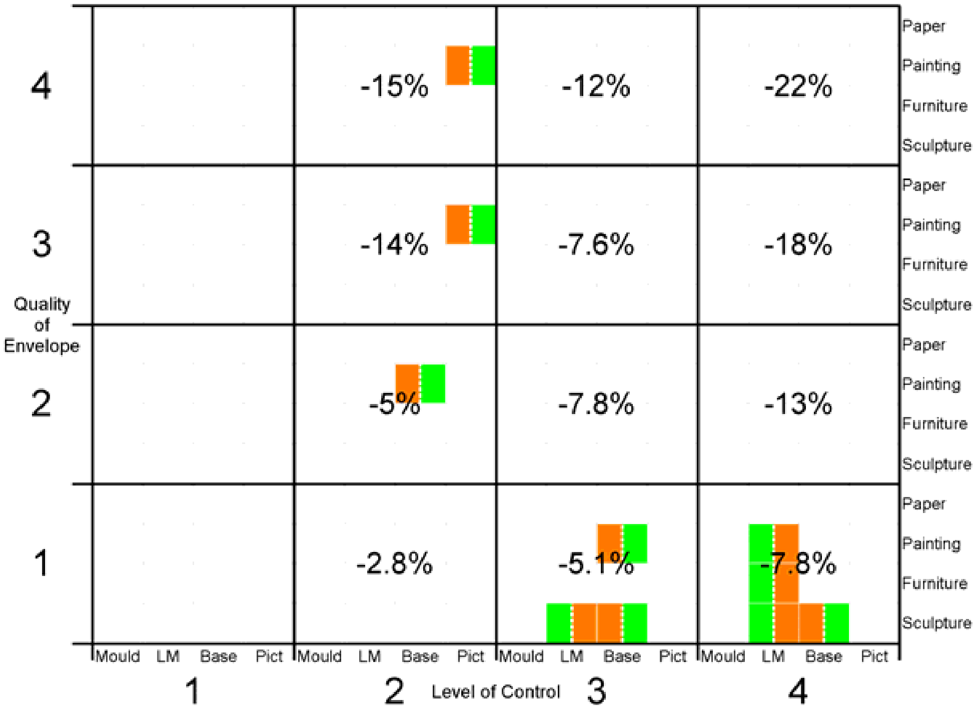


Figure 7.15: Comparison of risks and energy use, original (left) and variant G (right); only differences are displayed. Low risks are colored green, moderate risks orange and high risks red.

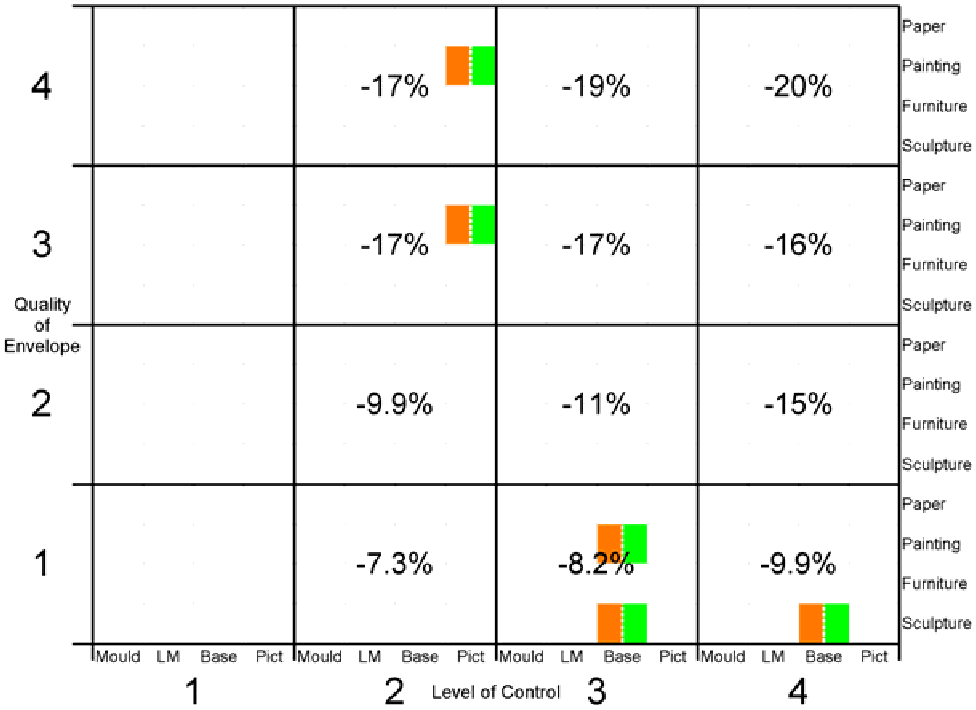


Figure 7.16: Comparison of risks and energy use, original (left) and variant H (right); only differences are displayed. Low risks are colored green, moderate risks orange and high risks red.

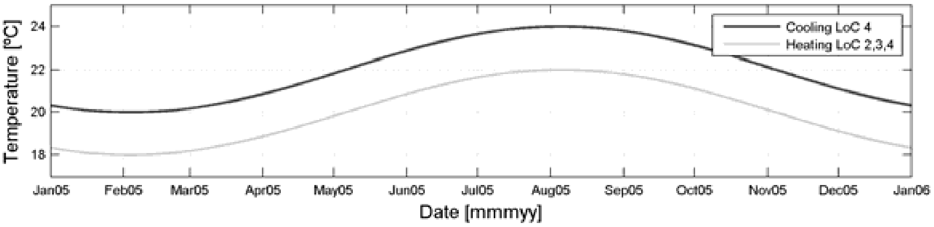


Figure 7.17: Set point for temperature in variant E.

The risks on damage to the pictorial layer of the panel painting are reduced for LoC 2 in combination with QoE 3 and 4. This is due to the smaller seasonal change in RH: lower temperature set point in winter prevents low RH values, while a higher temperature set point in summer prevents high RH values. This is only true in cases in which no (de)humidification is performed. Conservation heating [Neuhaus et al, 2007] is based on this principle. Risk on damage to the base material is also improved.

The LM decreases in QoE 1 and LoC 4; the leaky envelope causes summer temperatures to be slightly higher and also the RH is above the desired value.
Although the average temperature does not change, the energy use is reduced considerably. Savings are highest in LoC 4 & QoE 4: 20%. In QoE 1 & LoC 2 savings are only 2.8%. A higher QoE leads to a larger saving, while also the initial energy use was smaller. A higher LoC leads also to a larger saving, but in this case the initial use was higher.

7.4.4. Seasonal change in relative humidity set point

In variant F the RH set point is varied over the seasons. The amplitude is 10%RH (the maximum seasonal shift allowed in ASHRAE classes As and B). LoC 3 in the basic case used 40% as the humidification set point: this value is changed into 30% in winter and 50% in summer. For dehumidification, 60% was used: this is now changed into 50% in winter and 70% in summer. The difference in set point between humidification and dehumidification therefore remains 20% throughout the year. For LoC 4 this difference is 4%. Combined with a seasonal change of 10% the set point for humidification varies from 38% in winter to 58% in summer; for dehumidification the set point varies from 42 to 62% in winter and summer, respectively. Figure 7.18 shows these set points.

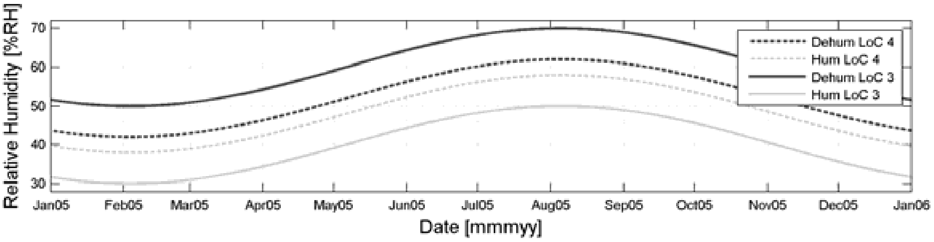


Figure 7.18: Set point for relative humidity in variant F.

Figure 7.14 compares simulation results of the seasonal adjustment in RH set point with the basic model results. The lifetime multiplier decreases in QoE 3 & LoC 3 and in QoE 1 & LoC 4, indicating that risks

for chemical degradation increase. There is more risk on damage to the pictorial layer of paintings for QoE 1 & LoC 3, but less risk for the base material of wooden sculptures. All other risks remain the same.
The effects on energy use are not uniform: in some combinations energy can be saved, while in others energy consumption increases. In LoC 4 the energy use decreases, as does the energy use in LoC 3 & QoE 1 and 2. In LoC 3 & QoE 3 and 4 however the energy use increases. The high summer RH set point and the small infiltration rate cause high indoor temperatures; extra humidification in summer is needed.

7.4.5. Seasonal change in both T and RH set points

Another option is to combine seasonal set points for T and RH simultaneously: variant G. In winter, a lower temperature and a lower RH set point are incorporated, while in summer higher temperatures and RH values are allowed. This is a combination of set points as described in 7.4.3. and 7.4.4. Figure 7.19 shows both set points.

Results for variant G are displayed in figure 7.15. For LoC 2 the results are similar to figure 7.13: less damage is expected for panel paintings. For some objects in QoE 1 & LoC 3 and 4 the LM decreases. This has to do with the combined raising of T and RH: the LM lowers considerably in summer and is not entirely compensated for during winter. Risks on damage to the base material of wooden sculptures decrease in QoE 1 & LoC 3 and 4.
Combining seasonal changes in both set points is only a good idea in LoC 4 and in LoC 3 combined with QoE 1 and 2 in terms of energy use. The other combinations show an improvement when compared to the basic model, but it should be noted that changing the temperature set point only – without RH set point adjustment – shows similar or better results for the energy use.

7.4.6. Temperature set point based on outdoor conditions

Instead of a sine curve, actual weather conditions can be used to determine set points. A number of museums in the Netherlands and many office buildings use an average outdoor temperature to calculate the indoor temperature set point. For variant H an example of an adjustment is displayed in figure 7.20. An outdoor average temperature over the last 3 days is calculated; in case of an average of 5ºC or lower a set point of 18ºC indoors is applied; 20ºC or higher leads to 22ºC in the building. The set point increase is proportional to the average outdoor temperature increase. This leads to a lower energy use and also to a smaller HVAC capacity needed.

Figure 7.21 shows the actual set points for temperature during this simulation. The average temperature for heating is 19.7ºC, which does not differ much from the 20ºC fixed set point in the basic simulation.

Figure 7.16 shows the implications for preservation risks. In LoC 2, risks on damage to the pictorial layer of paintings decrease for the same reasons as described in paragraph 7.4.3. Risks on damage to the base materials of objects is reduced in QoE 1 & LoC 3 and 4 No increase in risks is observed. Energy savings are higher than when using a sine curve; the set points resemble the outdoor conditions more than in case of a sine curve.

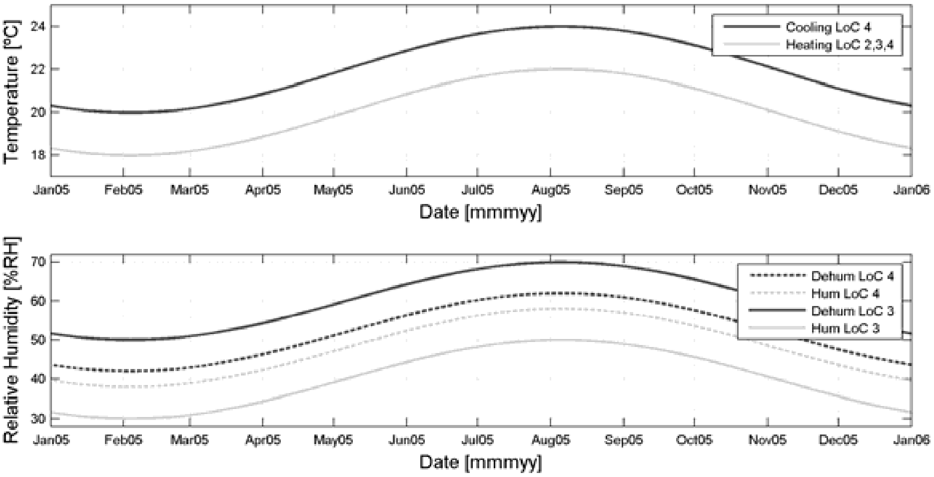


Figure 7.19: Set points for temperature and relative humidity for variant G.

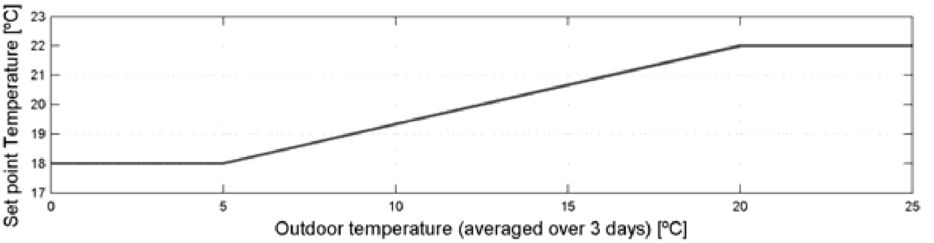


Figure 7.20: Temperature set point determination based on outdoor temperature.

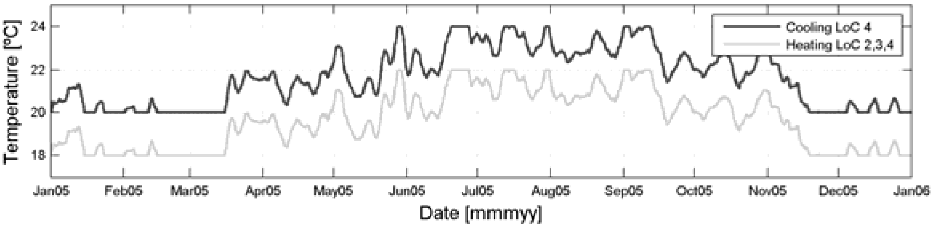


Figure 7.21: Set point for temperature, calculated based on outdoor temperature for variant H.

7.4.7. Temperature set point based on outdoor conditions, RH on sine curve

RH needs to be fairly constant in order to provide for enough safety for the objects. Basing the indoor RH directly on the outdoor RH or humidity mixing ratio will not result in a stable climate. However, when T is based on the outdoor conditions, RH can be based on a sine curve: variant I. In figure 7.22 set points for T and RH are presented.

Results are displayed in figure 7.23. The maximum energy saving – up to 23% – is reached in QoE 4 & LoC 4. In all other combinations savings are in between 7.3 and 19%. Risks do not change much; again for

LoC 2 damage to the pictorial layer is less likely, while for QoE 1 & LoC 3 and 4 less risk to the base material of sculptures and paintings is observed. The LM in QoE 1 & LoC 4 slightly decreases.

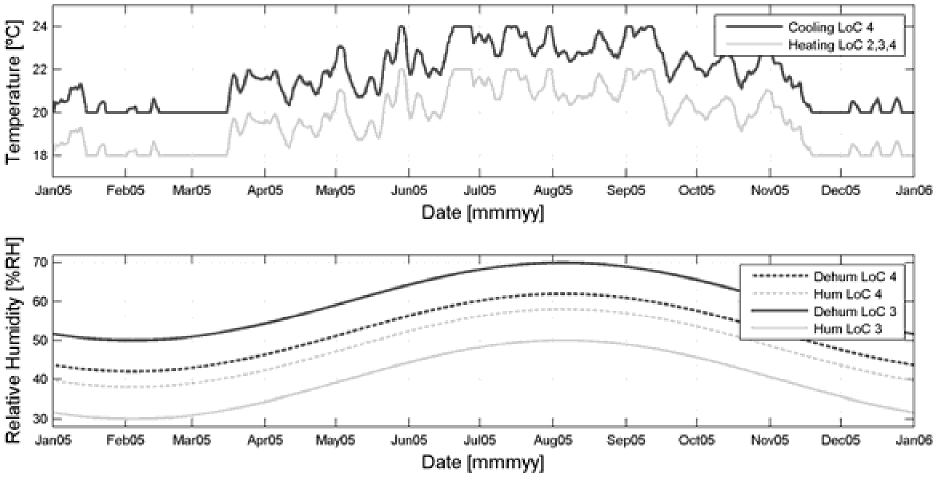


Figure 7.22: Set points for temperature and relative humidity for variant I.

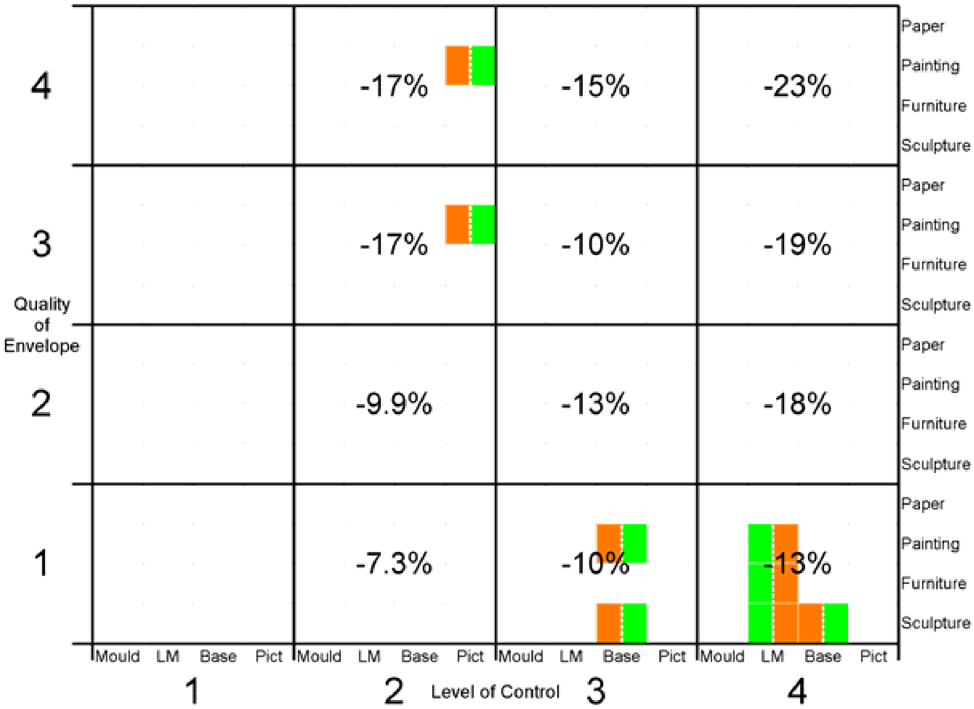


Figure 7.23: Comparison of risks and energy use, original (left) and with T set point based on outdoor T and RH set point based on a sine curve (variant I) (right); only differences are displayed. Low risks are colored green, moderate risks orange and high risks red.

7.4.8. Energy use

Figure 7.24 shows for each combination of LoC and QoE the amount of energy that is saved or consumed extra when compared to the basic model. Energy is consumed by heating, cooling, humidification and dehumidification, which are combined using a system efficiency (useful energy delivered divided by the total energy consumed) of 100%. In practice, the energy use will also depend on the type of systems used and their efficiency. The percentage of energy is displayed for simulation A up to I, as described in table 7.4.

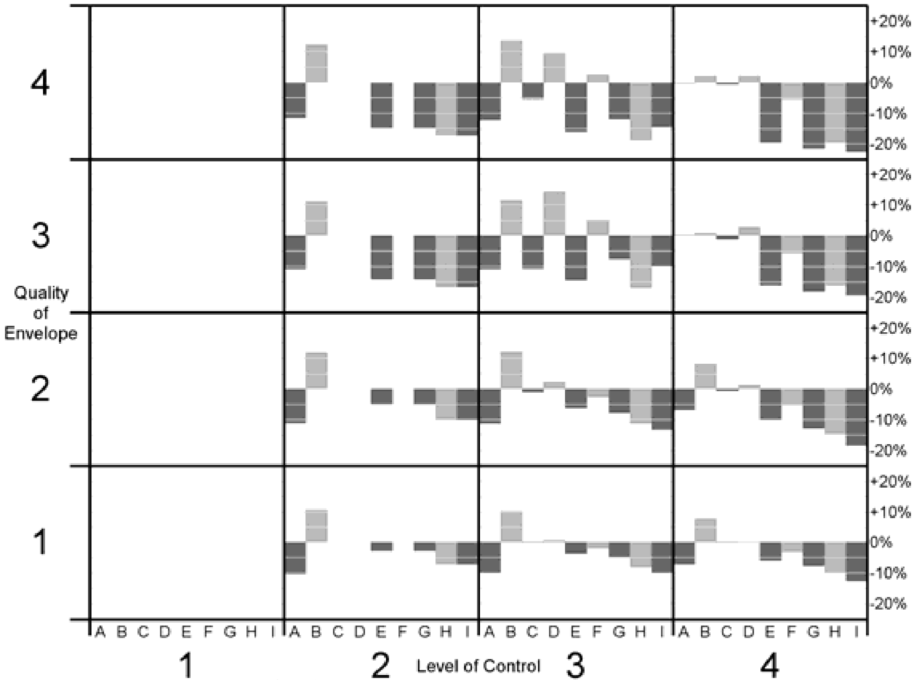


Figure 7.24: Energy saving in percent by changing set points.

Changing fixed temperature set points by decreasing temperature with 1°C (variant A) allows an energy saving of 10 to 12 % in LoC 2 and 3, regardless of the building type. In LoC 4, in which also cooling is incorporated, energy savings are less, to about 5% in QoE 1 and 2. In QoE 3 and 4 savings are practically zero because of the increased cooling load. In well insulated buildings with cooling, lowering set points is not as beneficial as in buildings without cooling. An option is to increase the dead band (bandwidth in which no heating or cooling is required) by lowering temperature heating set point without lowering cooling set point, but this bandwidth is restricted in most climate regulations [e.g. ASHRAE, 2007 & Jütte, 1994].

Increasing temperature set point (variant B) with 1°C shows an increase in energy use of 0.9 to 14%.

Decreasing the RH set point (variant C) with 5% has no effect on LoC 2, since no (de)humidification is installed. About 0.6 to 5% can be saved in LoC 3 and 4. Increasing RH set point (variant D) shows an increase in energy use for all LoC 3 and 4: 0.5 to 15% more energy is needed. Only in LoC 4 and QoE 1 a little energy is saved: 0.11% because of the leaky envelope and the RH that better suits the outdoor conditions.

Applying a sine curve for temperature (variant E) saves energy in all combinations of QoE and LoC: 2.8 up to 20%. Energy savings increase when increasing QoE. This means that even – and especially – in well insulated buildings it is useful to use a lower winter set point and a higher summer set point.

Applying a sine curve for relative humidity (variant F) reduces energy use in LoC 4 (2.6 to 5.7%) and in LoC 3 / QoE 1 and 2. In QoE 3 and 4, however, more energy is used: 2.6 to 5.2%. This is caused by the air tightness: the influence of weather conditions is so little that the RH neither drops to a very low level during winter, nor rises to a very high level during summer. Extra effort from the climate system is needed to create this seasonal change in set point.

Applying a sine curve for temperature and relative humidity combined (variant G) shows similar results as variant E. All combinations show a decrease in energy use, but the effect is largest buildings with a high QoE.

In variant H the outdoor temperature determines the temperature set point. All combinations show energy savings of 7.3 to 20%. The effect is higher than when a sine curve is applied (variant E), because the set point fits better to the actual conditions. The outdoor climate cannot be exactly reproduced by a sine curve.

When applying an outdoor dependent temperature set point and a sine curve RH set point (variant I), energy savings are even a bit higher than in the previous simulation (H): 7.3 up to 23% savings can theoretically be realized.

Table 7.5: Most promising set point settings for energy saving for each combination of QoE and LoC.

Variant	Optimal setting (percentage saving)	Second best setting (percentage saving)
QoE 1 / LoC 1	-	-
QoE 1 / LoC 2	T set point - 1°C (11%)	Set point T based on weather (7.3%)
QoE 1 / LoC 3	T set point - 1°C (10%)	Set point T based on weather; RH on sine curve (10%)
QoE 1 / LoC 4	Set point T based on weather; RH on sine curve (13%)	Set point T & RH based on sine curves (7.8%)
QoE 2 / LoC 1	-	-
QoE 2 / LoC 2	T set point - 1°C (11%)	Set point T based on weather (9.9%)
QoE 2 / LoC 3	Set point T based on weather; RH on sine curve (13%)	T set point - 1°C (11%)
QoE 2 / LoC 4	Set point T based on weather; RH on sine curve (18%)	Set point T & RH based on sine curves (13%)
QoE 3 / LoC 1	-	-
QoE 3 / LoC 2	Set point T based on weather (17%)	Set point T based on sine curve (14%)
QoE 3 / LoC 3	Set point T based on weather (17%)	Set point T based on sine curve (15%)
QoE 3 / LoC 4	Set point T based on weather; RH on sine curve (19%)	Set point T based on weather (16%)
QoE 4 / LoC 1	-	-
QoE 4 / LoC 2	Set point T based on weather (17%)	Set point T based on sine curve (15%)
QoE 4 / LoC 3	Set point T based on weather (19%)	Set point T based on sine curve (16%)
QoE 4 / LoC 4	Set point T based on weather; RH on sine curve (23%)	Set point T based on weather (20%)

To conclude, the best and second best options for saving energy are given in table 7.5. In monumental buildings without any changes to the envelope just lowering temperature is very effective. In well insulated building envelopes with full HVAC systems sine curve set points are most effective. In other buildings the set point should be related to the outdoor temperature; in case of humidity control RH set point is best controlled by applying a sine curve.

7.5. VENTILATION RATE

The influence of ventilation rate on both fluctuations in indoor climate and energy use is high. A high ventilation rate provides a high volume of outdoor air entering the exhibition space. In case of an unconditioned building, this outdoor air influences the stability of temperature and RH. Since the RH is the most important parameter for risk on mechanical damage to objects on display, the hourly, daily and weekly changes (average and standard deviation) in RH are displayed as a function of ventilation rate in figure 7.25. Only the combination of QoE 1 and LoC 1 is displayed.

In churches, ventilation rates are usually 0.7 h^{-1} in case of a wooden vault and 0.1 h^{-1} in case of a stone vault [Schellen, 2002]. In other monuments ventilation rates are higher than in churches, often in between 0.2 and 2: the rooms are smaller and therefore the ratio between volume and surface is higher, resulting in more infiltration of outdoor air and a higher ventilation rate. It is, however, largely dependent on the type of envelope.

It can be seen from figure 7.25 that the graph for weekly changes is the steepest in between 0.1 and 1 h^{-1}; the influence on stability of the RH is high. Below 0.1 h^{-1} the climate is quite constant. Rates larger than 10 h^{-1} resemble the Dutch weather (displayed on the right); for stability 0.1 h^{-1} or a bit lower is recommended. This might explain why delicate objects lasted for centuries in old buildings: the changes in RH are usually not so high.

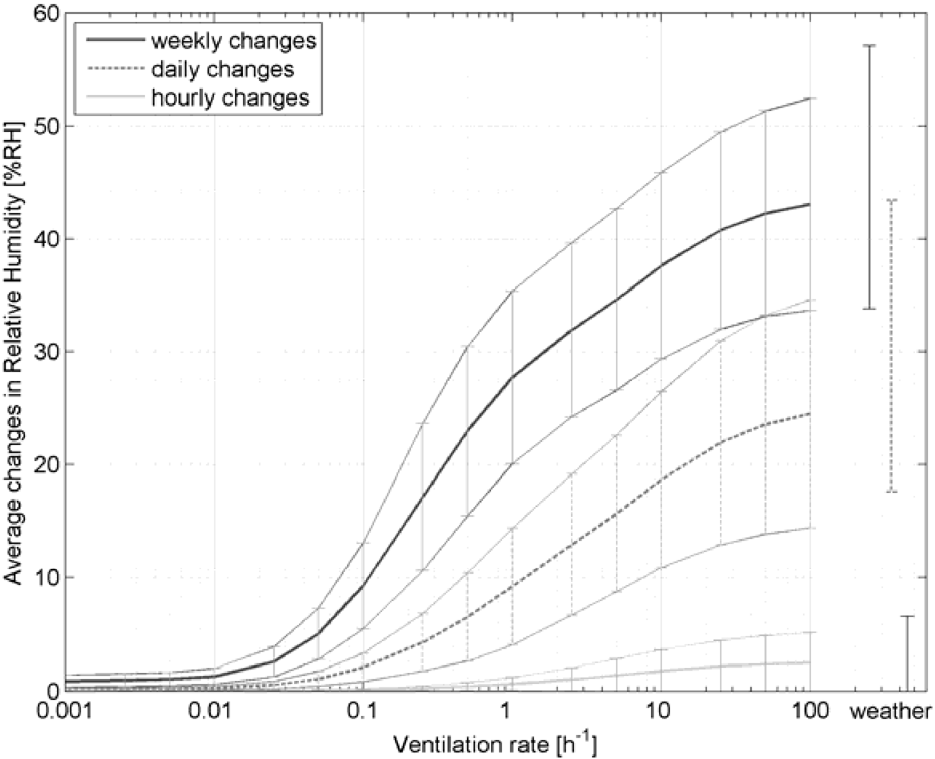


Figure 7.25: Average and standard deviation in RH fluctuations on hourly, daily and weekly basis as a function of ventilation rate, for QoE 1 and LoC 1.

It is important to note that small ventilation rates are risky in case moisture sources (e.g. leakage or many visitors) are present. The indoor RH will rise to very high values, with an increase in risk on mould. On the other hand, for the building small ventilation rates might be safer than high ventilation rates: moist walls in e.g. a basement might dry faster, causing more salt efflorescence and damage to the wall.

In case a climate system is present to compensate for the changes in RH, e.g. for QoE 4 and LoC 4, the changes are kept small but the energy use is affected. This is displayed in figure 7.26. A double logarithmic scale is used. The graph shows 2 asymptotes: a horizontal representing transmission losses (these are not affected by the ventilation rate) and a 45° line indicating that for high ventilation rates the relation between energy use and ventilation rate is linear. The optimum, based on energy use and changes to the building, lies somewhere around 0.1 h^{-1}.

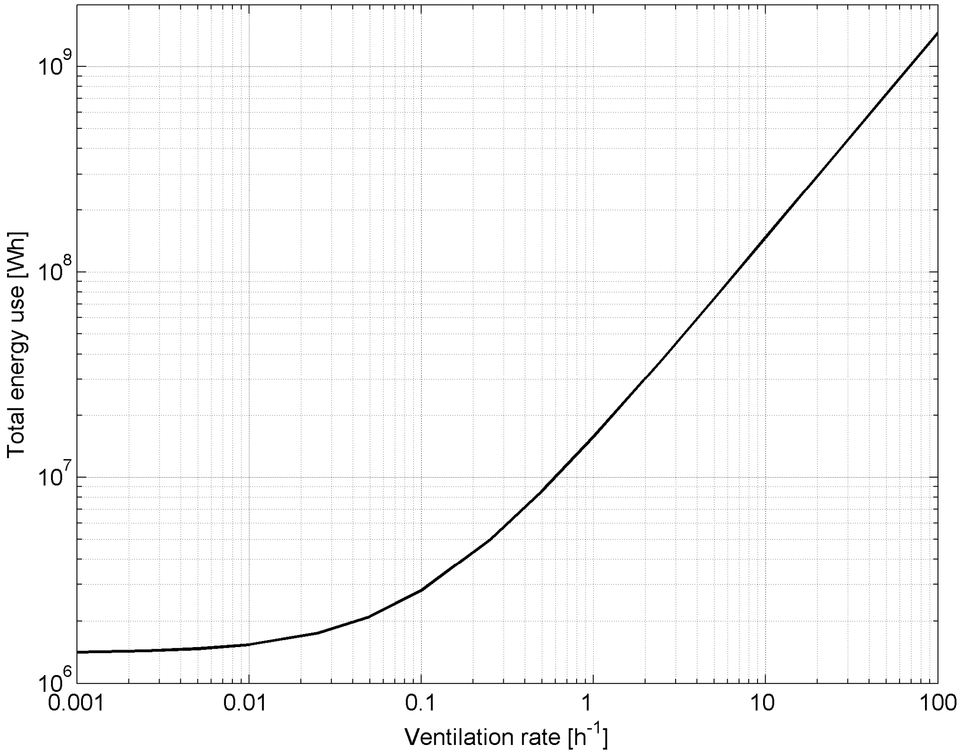


Figure 7.26: Total energy use when keeping the indoor climate at 18 to 22°C and 48 to 52%RH as a function of ventilation rate, for QoE 4 and LoC 4.

When many people visit the museum, ventilation is required to supply fresh air to the people. In a storage situation, in which no visitors are present and staff is only present for short periods of time, it is recommended to keep the ventilation rate as low as possible. This will improve the climatic stability of the storage area and reduce the amount of energy use. For objects that emit volatile components care must be taken that these components are removed by recirculation and filtering of the air.

7.6. BANDWIDTH

Marx Ayres concluded that the bandwidth of acceptable RH fluctuations does not make much difference in energy use [Marx Ayres et al., 1989]. Ascione however found that changing the admitted indoor climate from 50 ± 2% to 50 ± 10% energy savings of 10% are obtained [Ascione et al., 2009]. The latter is also found by Artigas. Based on measurements, he deduced an exponential relationship between variance in the indoor climate and energy consumption: as the variance increased the costs decreased [Artigas, 2007].

The simulation model of QoE 4 and LoC 4 is used to estimate the amount of energy use for humidification and dehumidification. Results are displayed in figure 7.27. The set point is kept at 50%; the bandwidth is increased from 0 to 10% in steps of 1%. This means, that for a bandwidth of 10% the RH is in between 40% and 60%.

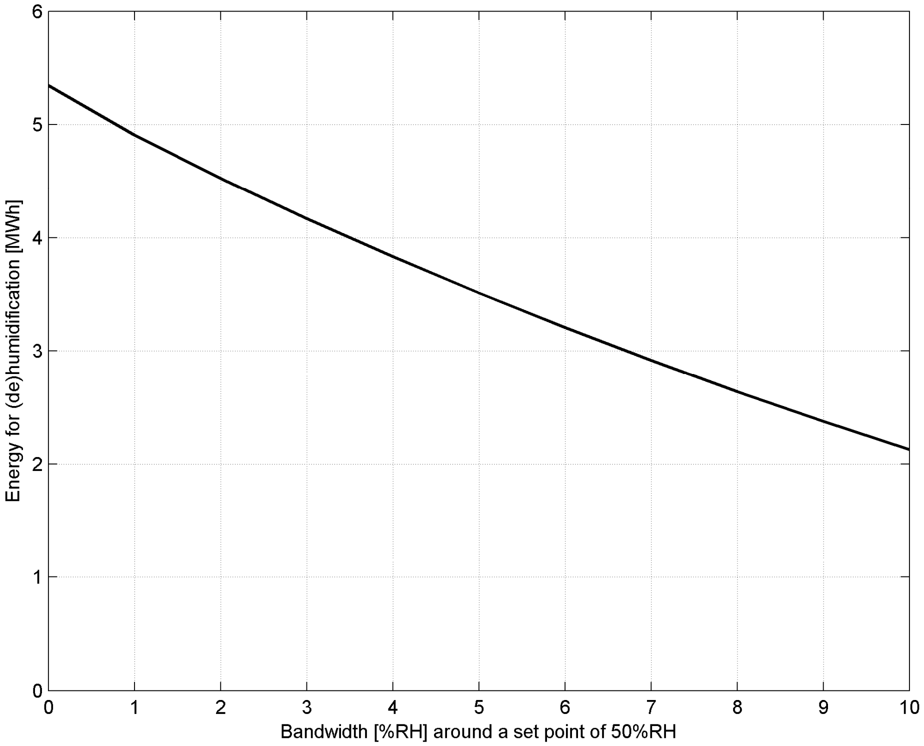


Figure 7.27: Energy needed for humidification and dehumidification by changing the bandwidth around a set point of 50%RH, for QoE 4 and LoC 4.

Figure 7.27 shows that a larger bandwidth reduces the amount of energy needed. It is important to note that this simulation only takes into account the energy needed in the space itself, moreover the indoor climate is fully mixed. In reality, when a narrow bandwidth is strived for, the climate system runs from humidification mode into dehumidification mode and back intermittently. This will highly affect the energy use because it has a cancelling effect. Dehumidification for 1 minute and humidification for the next minute will not change the indoor climate much, except locally near the inlets. Creating a so-called dead band in between will minimize this effect and saves energy and cost.

7.7. CONCLUSIONS AND RECOMMENDATIONS

Simulations show that a strict climate (LoC 4) in a primitive building (QoE 1) is not a sensible option. Even in the case where the system is able to achieve the set points desired, the energy consumption is high and near the envelope objects are exposed to higher risks. Also the building experiences high risks near thermal bridges, e.g. condensation, fungal growth and wood rot.

Ventilation rate plays an important role on energy use. In well insulated buildings the amount of glazing becomes important; solar heat gains easily lead to overheating. In monumental buildings, thick walls are an advantage because of the buffering of temperature and humidity and insulating properties. By adding extra insulation or an extra wall on the inside some of these advantages will be lost.

Energy savings and preservational qualities do not conflict in most cases. Creating a more stable climate, e.g. by reducing solar gains, will in most cases improve preservation conditions and lead to less energy use.

Going from LoC 1 to LoC 2 reduces risks on fungal growth and in some cases also reduces risks for damage due to mechanical degradation. Going to LoC 3 reduces those risks even further, but in buildings with an old envelope the limit of improvement is easily reached: because of the monumental status few changes to the envelope are allowed. From LoC 3 to LoC 4 shows no improvement, even though summer temperatures remain lower and human comfort will be higher.

Going from QoE 1 to 2 will only improve preservation in case a climate system is present (LoC 3 or 4). Going to QoE 3 reduces risks on fungal growth, but due to higher temperatures the lifetime multiplier decreases. Going to QoE 4 leads to a minimum reduction in risks and, in case of LoC 1 and 2, a small increase in lifetime multiplier.

Improving QoE without changing LoC will save energy, improve preservation near the envelope and increase comfort. Improving LoC without changing QoE will increase energy use, but risks are not reduced. Collection risks in QoE 2, 3 and 4 combined with LoC 3 and 4 do not differ much, so when going for the most state-of-the-art solution more investments in building and climate system do not lead to less risk.

Lowering the annual mean temperature set point by 1°C saves energy and increases the object's lifetime. Only in well insulated buildings with higher internal loads savings will be cancelled due to increased cooling loads.

Risks can be reduced and energy saved by changing set points to follow the outdoor climate. Differences between indoor and outdoor climate are reduced so less energy is needed without increasing the climate risks for the collection.

The influence of set points is nearly as important as the type of building and climate system. An old building without any changes made to the envelope with carefully chosen set points can have similar energy use and preservation risks as a much better building with illogical set points. When looking at the ASHRAE table (table 3.1 in this thesis), the most optimal climate guidelines in the Dutch situation are B (in unchanged buildings) and As (in new or improved monumental buildings); the combination between collection risks and climate system energy use are best balanced in these climate classes. In is advisable to use the entire bandwidth specified; risks will not increase, but energy savings will be high.

This leads to the conclusion that, for the Dutch situation, in old unchanged buildings (QoE 1 or 2) a simple system (LoC 2 or 3) can be used in order to achieve ASHRAE class B. In new museums (QoE 4) a more elaborate system can be used (LoC 4) with set points that comply with ASHRAE class As.

Conclusions & recommendations 8

This final chapter first answers the research questions as presented in Chapter 1. Then some general conclusions are drawn. Finally some recommendations are made for museum management and for further research.

8.1. RESEARCH QUESTIONS

1. When evaluating the preservation qualities of an indoor climate, are climate guidelines a good substitute for an object oriented approach?

In the past climate guidelines – or to be more precise: T and RH specification – where very often used. It was assumed that low RH values caused dehydration, high RH values caused fungal growth and large fluctuations in RH would lead to fracture. Still climate guidelines can be very useful in case no knowledge is available on the behavior of objects due to the local climatic environment. Guidelines tend to be on the safe side; more fluctuations in temperature and relative humidity can often be tolerated without increasing degradation risks.

Climates that endanger objects will also show bad results when compared with climate guidelines; when guidelines are met also risks will be limited. The only problem that exists is what happens to the objects when a guideline is not met 100% of time. Does this directly lead to a high risk on degradation? A brief excursion to a very low RH might not be experienced by an object with a long response time, but for another object with a short response time it may cause large gradients over the material and lead to damage. This asks for a more detailed approach, in which object behavior is included.

2. Is it possible to predict preservation qualities using measured or simulated indoor climate and how can this be done?

Yes, it is possible to predict preservation using indoor climates. This can be done in different ways. In chapter 3 a method – the general climate risk assessment method – is presented in which temperature and relative humidity series are used to determine the percentage of time the indoor climate is within the bandwidth of the ASHRAE climate classes. These climate classes are used to address risks for various degradation processes. In chapter 5 another method – the specific climate risk assessment method – is introduced to predict the climate experienced by four specific objects using their response times near the surface and in the bulk of the material. This experienced climate is then used to predict risks on three degradation processes, specific for each object. Chapter 6 addresses differences in results for both methods, which are mainly caused by the fact that short periods outside the bandwidth increase the expected risks, which is not taken into account in the general climate risk assessment method.

3. What influence does the building type have on preservation of objects in the Dutch situation?

Most objects are subjected to the air conditions as experienced in the center of a room. Also most measurements discussed in chapter 4 and 6 showed conditions at a distance from the building envelope. In practice very little differences in preservation risks are encountered for different building types when these average air conditions are examined. This is mainly caused by the climate systems that compensate for the poor quality envelope. It should be noted, however, that close to the building envelope conditions will differ from the average conditions: effects such as condensation are regularly observed. In monumental buildings these differences are larger than in newly built or renovated museums with insulated walls. Due to these differences more risks are introduced 1) for the envelope and 2) for objects placed near the envelope. Condensation and fungal growth can be expected when the envelope does not meet the thermal requirements in combination with set points that do not take into account weather conditions.

In case of a double wall risks to the original envelope may still be present. The effects of the indoor climate on the envelope cannot be seen directly, so it is advised to monitor the conditions in between envelope and double wall by doing measurements or by regular inspection.

4. Are simulated indoor climates as accurate as measured indoor climates in predicting preservation?

For a correct simulation it is important to do a validation with climate measurements. A model is never able to fully reproduce measured data, but the general indoor climate may be predicted very well. The match with the 'specific climate risk assessment method' is very promising. Because object response times are included in this method it is not so important for the simulation model to exactly reproduce the indoor climate, but predict the for preservation relevant statistical properties of the expected indoor climate.

It is important, however, to include the object's position in the building. The simulation model also calculates microclimates close to cold surfaces. This has a huge influence on object preservation since these microclimates are more extreme.

5. What physical parameters of the building have the most influence on the prediction of preservation?

Chapter 7 concludes that by reducing the surface area of the envelope, decreasing transmission losses through the envelope and lowering the infiltration the natural indoor climate will become more stable. Of these parameters, ventilation rate has the largest effect. In buildings in which the natural climate is improved by a climate system, these parameters are only of influence on energy use and on degradation risks close to the envelope. Most important for preservation of objects is the 'Level of Control'. Regardless of the building type, if temperature and RH are controlled sensibly the best preservation quality is possible. The energy use, however, is most dependent on 'Quality of Envelope'. Climate systems in old buildings might consume 8 times more energy when compared to systems in new buildings, just because of differences in the envelope.

6. What is the influence of set points for temperature and relative humidity on the degradation of objects and the energy use?

Chapter 7 shows that the preservational quality on an indoor climate does not only depend on the quality of the envelope and the type of climate systems used: also the set points contribute to this quality. Especially chemical degradation is influenced by the choice for set points. Also mechanical degradation can be reduced by carefully selecting these set points.

A single set point that is used year round puts the most stress on climate systems in terms of capacity needed and energy used. Also the most danger is presented to the old envelope. Chapter 7 shows that a set point that follows the weather conditions fits best to most combinations of Quality of Envelope and Level of Control: minimal changes in comfort and preservation are encountered while saving about 25% of energy. Moreover, in case of a system malfunction, a set point more close to the outdoor conditions provides more safety.

8.2. GENERAL CONCLUSIONS

The matrix introduced in chapter 2 is very useful when adapting a museum building. The diagonal would be the most logical path for improvement of preservational properties and energy use: envelope, climate systems and set points should match.

Large deviations from the diagonal should not be considered. In practice, there are a lot of examples of problems arising due to a bad combination of Quality of Envelope and Level of Control. Often changes cannot be made to a monumental building because the look and feel of the building must remain original. The only option to improve the indoor climate is to apply a climate system. Also the incorporation of such a system might be challenging: ducted systems consume a lot of useful space and need to be installed in such a way that the change to the building is reversible. Because of the old envelope, the energy demand is high and the capacity of the climate system needs to be high. When also a narrow bandwidth in RH is strived for, problems caused by lack of capacity, system malfunctions and local climate conditions that deviate considerably from the average climate conditions can be expected.

It is important to consider the role of the museum management. The approach that it should be possible to place any object anywhere in the museum without risk is not realistic in a monumental building. Trying to create a risk free and comfortable environment will definitely damage the monument. Moreover, conditions near the envelope are not only harmful for the envelope itself but also for objects placed close to the envelope.

When taking into account the practical limitations of the building, such as the conditions near the envelope, still a very low risk indoor climate can be achieved. Delicate objects can be placed in display cases near inner walls or in the middle of rooms. Objects attached to the envelope should be placed at a distance, so that mould growth behind these objects is prevented. Additionally, also the set points used should match the weather conditions and the building: a seasonal adjustment in RH is usually safer for both building and objects. Extensive condensation and local mould growth due to a single set point used all year should be prevented.

In some museums the building is a very important part of the collection. Preventing risks for the building in general and the envelope in particular is the main goal. A safe climate for objects is less important. Most objects can be displayed without serious risks, but delicate artifacts should be placed elsewhere or extra measures need to be taken.

There are many useful tools available that can be used to determine the preservation quality of a museum indoor climate, e.g. the general climate risk assessment method as presented in chapter 3 and the specific climate risk assessment method introduced in chapter 5. These tools can be used to easily assess the quality on various positions in a museum. The results can be used to relocate delicate objects or to make some local changes in order to improve the quality of preservation.

8.3. RECOMMENDATIONS

The recommendations are split into 2 parts: the first paragraph contains recommendations to museum staff, system engineers, while the second part is about further research.

8.3.1. Recommendations to museums

Sebor states that collections staff must define their needs and start a dialog with the HVAC engineer, so he can design a climate system [Sebor, 1995]. This is not the most optimal path, since collection staff mostly have little knowledge about climate systems, while the engineer does not know much about collection needs. Carefully balancing building, set points and climate system is essential for ending up with a reasonable climate; a multidisciplinary approach is needed.

Please make sure that the climate systems engineer knows how to design a system for a museum. A museum is not an office, because priority should be on RH and not on temperature. Most engineers find it difficult to design such a system and simply copy a system that works nicely in an office. This is a recipe for disaster. Moreover, system should be designed without overcapacity: the climate system is turned on all year; in case of weather extremes it is usually safer to keep the indoor climate closer to the outdoor climate.

Climate monitoring should be available for museums, also for museums that have a simple climate system. By monitoring temperature and RH it is clear when conditions start to get out of hand and extra measures need to be taken, e.g. extra humidification or a lower temperature set point during winter. For museums with an advanced climate system, monitoring is needed to guarantee the functionality of the climate system with independent sensors. In case of malfunctioning, early measures can be taken to prevent serious problems. The monitored data can also be used for risk assessment, such as the general or specific climate risk assessment method explained in this thesis.

Please make sure that the indoor climate in a museum is reasonable for the monumental building and a majority of the objects. Delicate objects can be put in display cases instead of trying to adjust climate conditions to a narrow bandwidth for the entire building.

Loan agreements also contain desired climate conditions. If the lending museum specifies very strict conditions, please be aware that they cannot live up to these specifications themselves. Ask for their monitoring data and use this to negotiate.

8.3.2. Recommendations for further research

To complete the 'specific climate risk assessment method', modeling on object level can improve risk prediction. By using an advanced model that takes into account changing materials properties (e.g. the hygroscopic curve), stresses in materials can be calculated and damage predicted. The universities of Krakow and Eindhoven are currently working on this.

The specific climate risk assessment method could be extended by adding other objects. Also the influence of cracks in the decorative layer of objects should be taken into account. In the end, a library of objects with varying degrees of damage could be created, so an analysis is possible for a certain mixed collection.

It would be useful to use the model presented in chapter 7 by applying the climate the Intergovernmental Panel on Climate Change (IPCC) predicted for the next century. This gives an estimate of risk to objects because of a changing climate.

Few museum objects are placed in exhibition rooms. Most objects are in storage areas in other parts of the museum or in specialized depot buildings. The Dutch climate in combination with the latest building technology opens possibilities to create storage buildings that hardly use energy. Risks are minimal in such buildings, but employees are not comfortable when retrieving objects. When this is a frequent event this retrieval may be executed by an automated process.

Buildings react quite slowly to changes in climate (in the order of several hours or days). A slow climate system would be a logical choice to stabilize the indoor climate in a building. Short changes in use (groups of visitors or solar radiation) could be neutralized by buffer materials (old heavy envelope, plastered). Climate systems are dimensioned based on much faster effects (a cold day, a short heat up time) while they frequently operate at constant (or very slowly changing) set points. The current method of design of climate systems is not suitable to make a robust, simple system without much overcapacity. This design process should be looked at in detail, to better match the current museum practice.

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Nomenclature

ΔRHlong	Long changes in relative humidity (e.g. seasonal)
ΔRHshort	Short changes in relative humidity (e.g. hourly and daily)
ΔTlong	Long changes in temperature (e.g. seasonal)
ΔTshort	Short changes in temperature (e.g. hourly and daily)
A	ASHRAE climate class A
AA	ASHRAE climate class AA
ab	external solar radiation absorption coefficient
As	ASHRAE climate class As: class A with allowed seasonal change in RH
B	ASHRAE climate class B
Beta	Tilt (90° = vertical)
BMS	Building Management System
C	ASHRAE climate class C
CEC	Climate Evaluation Chart
CF	Convection Factor
CFh	Convection Factor of the heating system
CFi	Convection Factor of internal heat sources
CFr	Convection Factor without sun blinds
CFrw	Convection Factor with sun blinds
CFs	Factor that determines whether temperature control is on air or comfort temperature
CFz	Convection Factor of solar radiation due to furnishings
Cool	Cooling
D	ASHRAE climate class D
d1	thickness of material layer 1
d2	thickness of material layer 2
d3	thickness of material layer 3
d4	thickness of material layer 4
Deh	Dehumidification
dRd	average daily changes in relative humidity
dRh	average hourly changes in relative humidity
dRs	seasonal changes in relative humidity
dRw	average weekly changes in relative humidity
dTd	average daily changes in temperature
dTh	average hourly changes in temperature
dTs	seasonal changes in temperature
dTw	average weekly changes in temperature
eb	external long wave emissivity coefficient [-]
Ecooling	energy needed for cooling
Edehum	energy needed for dehumidification
Eheating	energy needed for heating
Ehum	energy needed for humidification
Ers	irradiance threshold for sun blinds [W/m^2]

eww	Efficiency for heat recovery
fbv	moisture storage factor
G?	Germination?
Gamma	Azimuth angle (south = 0°)
Gintc	Internal moisture production during closed hours
Ginto	Internal moisture production during opening hours
Heat	Heating
Hum	Humidification
ICN	Instituut Collectie Nederland
Infil	Infiltration rate $[h^{-1}]$
IPCC	Intergovernmental Panel on Climate Change
LM	Lifetime Multiplier [-]
LoC	Level of Control [-]
matID	Material identification number (in matpropf.m, HAMBASE)
Qintc	Internal heat gain during closed hours [W]
Qinto	Internal heat gain during opening hours [W]
QoE	Quality of Envelope
R-	Seasonal drop in relative humidity [%RH]
R+	Seasonal rise in relative humidity {%RH]
RCE	Rijksdienst Cultureel Erfgoed
Re	Resistance between wall and air, exterior $[Km^2/W]$
RH	Relative Humidity [%RH]
RHd	Relative Humidity set point for dehumidification [%RH]
RHh	Relative Humidity set point for humidification [%RH]
Ri	Resistance between wall and air, interior $[Km^2/w]$
Rm	Annual mean relative humidity [%RH]
Rmean	Annual mean relative humidity [%RH]
T-	Seasonal drop in temperature [°C]
T+	Seasonal rise in temperature [°C]
Tm	Annual mean temperature [°C]
Tc	Temperature set point for cooling [°C]
Tfc	Temperature set point for free cooling [°C]
Th	Temperature set point for heating [°C]
Tm	Annual mean temperature [°C]
Tmean	Annual mean temperature [°C]
TU/e	Eindhoven University of Technology
Tww	Set point for heat recovery [°C]
Uglas	U-value without sun blinds $[W/m^2K]$
Uglasw	U-value with sun blinds $[W/m^2K]$
Vol	Volume $[m^3]$
Vvmaxc	Ventilation rate during closed hours in case of free cooling $[h^{-1}]$
vvmaxo	Ventilation rate during opening hours in case of free cooling $[h^{-1}]$
vvminc	Ventilation rate during closed hours $[h^{-1}]$
vvmino	Ventilation rate during opening hours $[h^{-1}]$
ZTA	Solar gain factor without sun blinds [-]
ZTAw	Solar gain factor with sun blinds [-]

Definitions

Activation energy	The energy that must be overcome for a chemical reaction to occur
Conservation	Treatment and repair of individual objects to slow decay or restore them to a usable state
Creep	The tendency of a solid material to slowly move or deform permanently under the influence of stresses
Dry bulb temperature	The temperature of air measured by a thermometer freely exposed to the air but shielded from radiation and moisture
Frost day	A day in which the minimum temperature is equal to or below 0 °C [KNMI]
Ice day	A day in which the maximum temperature is equal to or below 0 °C [KNMI]
Infiltration rate	The number of times per hour that the total volume of a room or building is replaced with fresh outdoor air, not controlled and in most cases unwanted (through leakages in the envelope)
Lifetime Multiplier	The number of time spans an object remains usable when compared to a condition of 20°C and 50%RH
Local climate	A climate that differs from the average indoor climate because of the influence of disturbing factors such as solar radiation or colder surfaces
Microclimate	The climate very close to an object or in a disclosure surrounding the object
Mixed collection	Museum collection consisting of various objects of different materials and of different susceptibility to degradation processes
Operative temperature	Temperature experienced by objects and people in a room, calculated by taking 60% of the air temperature and 40% of the mean radiant temperature of all surfaces in the room
Preservation	Maintaining or restoring access to artifacts, documents and records through the study, diagnosis, treatment and prevention of decay and damage

Relaxation	The reduction of stresses over time caused by a permanent pressure
Response time	Time needed for an object to get to 95% of the end value in case of a step change in relative humidity
Room climate	Temperature and Relative Humidity in the center of the room or representative for a large part of the room (e.g. not close to colder surfaces)
Set point	The target value that an automated control system will try to reach
Summer day	A day in which the maximum temperature is equal to or over 25 °C [KNMI]
Tropical day	A day in which the maximum temperature is equal to or over 30 °C [KNMI]
Ventilation rate	The number of times per hour that the total volume of a room or building is replaced with fresh outdoor air, usually controlled by a mechanical system
Warm day	A day in which the maximum temperature is equal to or over 20 °C [KNMI]

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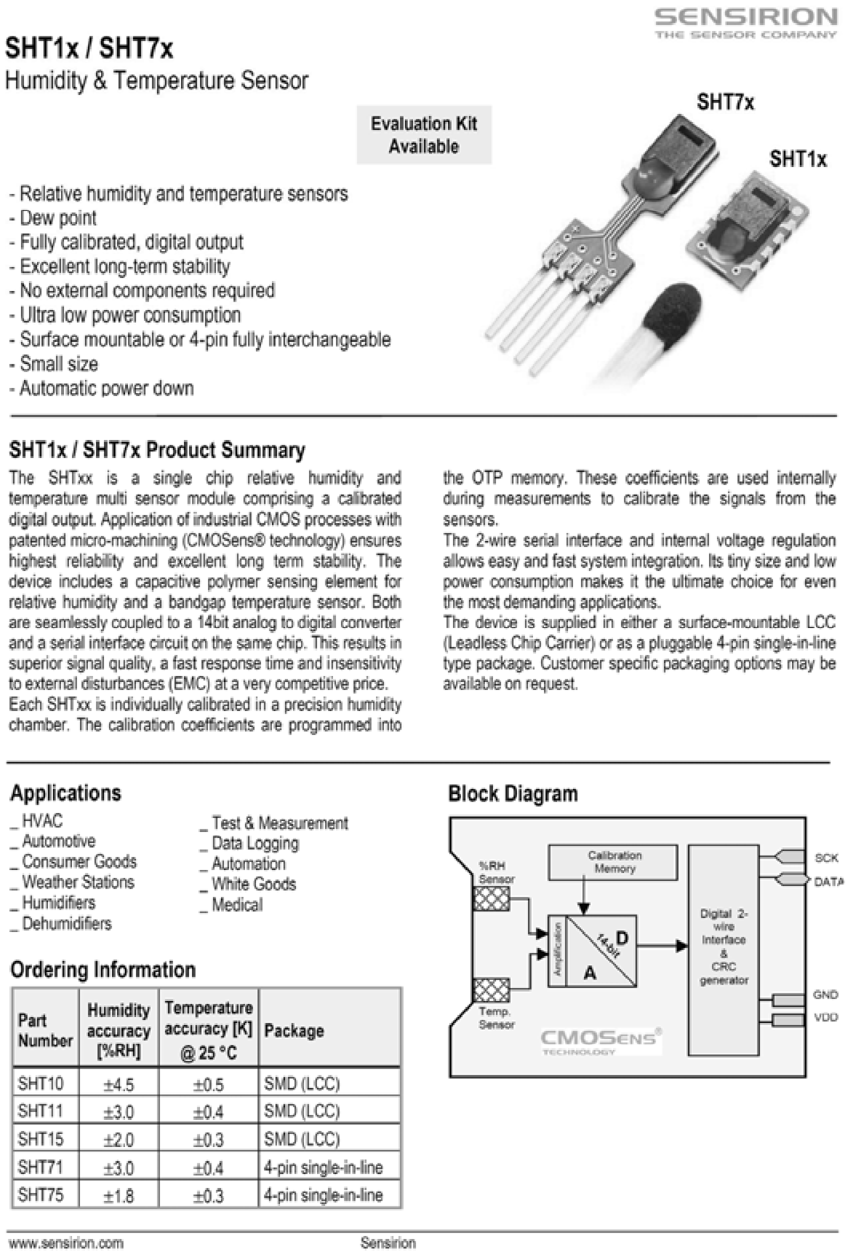
Appendix A: Sensirion specifications



SENSIRION
THE SENSOR COMPANY

SHT1x / SHT7x

Humidity & Temperature Sensor

Evaluation Kit Available

- Relative humidity and temperature sensors
- Dew point
- Fully calibrated, digital output
- Excellent long-term stability
- No external components required
- Ultra low power consumption
- Surface mountable or 4-pin fully interchangeable
- Small size
- Automatic power down

SHT1x / SHT7x Product Summary

The SHTxx is a single chip relative humidity and temperature multi sensor module comprising a calibrated digital output. Application of industrial CMOS processes with patented micro-machining (CMOSens® technology) ensures highest reliability and excellent long term stability. The device includes a capacitive polymer sensing element for relative humidity and a bandgap temperature sensor. Both are seamlessly coupled to a 14bit analog to digital converter and a serial interface circuit on the same chip. This results in superior signal quality, a fast response time and insensitivity to external disturbances (EMC) at a very competitive price.
Each SHTxx is individually calibrated in a precision humidity chamber. The calibration coefficients are programmed into the OTP memory. These coefficients are used internally during measurements to calibrate the signals from the sensors.
The 2-wire serial interface and internal voltage regulation allows easy and fast system integration. Its tiny size and low power consumption makes it the ultimate choice for even the most demanding applications.
The device is supplied in either a surface-mountable LCC (Leadless Chip Carrier) or as a pluggable 4-pin single-in-line type package. Customer specific packaging options may be available on request.

Applications

_ HVAC
_ Automotive
_ Consumer Goods
_ Weather Stations
_ Humidifiers
_ Dehumidifiers
_ Test & Measurement
_ Data Logging
_ Automation
_ White Goods
_ Medical

Ordering Information

Part Number	Humidity accuracy [%RH]	Temperature accuracy [K] @ 25 °C	Package
SHT10	±4.5	±0.5	SMD (LCC)
SHT11	±3.0	±0.4	SMD (LCC)
SHT15	±2.0	±0.3	SMD (LCC)
SHT71	±3.0	±0.4	4-pin single-in-line
SHT75	±1.8	±0.3	4-pin single-in-line

Block Diagram

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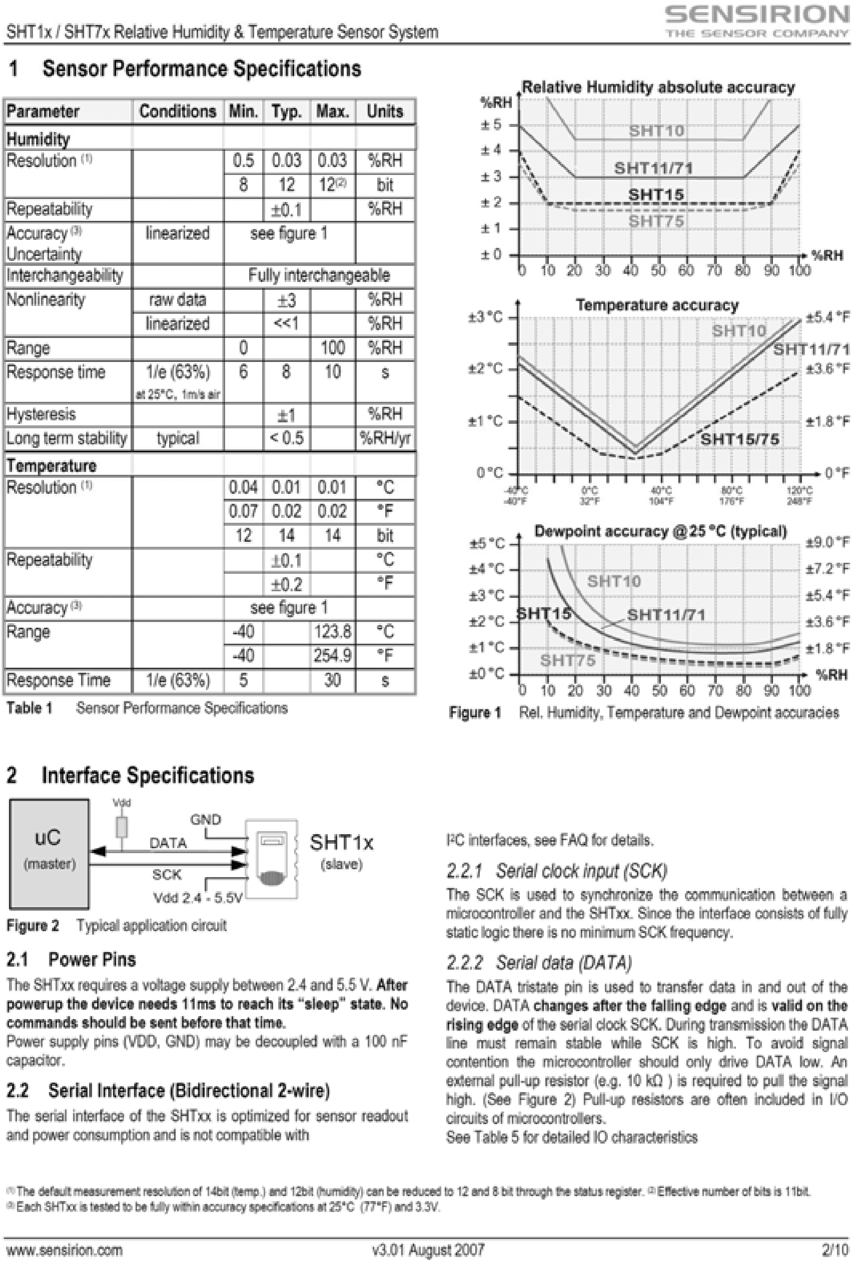

SENSIRION
THE SENSOR COMPANY

SHT1x / SHT7x Relative Humidity & Temperature Sensor System

1 Sensor Performance Specifications

Parameter	Conditions	Min.	Typ.	Max.	Units
Humidity					
Resolution (1)		0.5	0.03	0.03	%RH
		8	12	12(2)	bit
Repeatability			±0.1		%RH
Accuracy (3) Uncertainty	linearized	see figure 1			
Interchangeability		Fully interchangeable			
Nonlinearity	raw data		±3		%RH
	linearized		<<1		%RH
Range		0		100	%RH
Response time	1/e (63%) at 25°C, 1m/s air	6	8	10	s
Hysteresis			±1		%RH
Long term stability	typical		< 0.5		%RH/yr
Temperature					
Resolution (1)		0.04	0.01	0.01	°C
		0.07	0.02	0.02	°F
		12	14	14	bit
Repeatability			±0.1		°C
			±0.2		°F
Accuracy (3)		see figure 1			
Range		-40		123.8	°C
		-40		254.9	°F
Response Time	1/e (63%)	5		30	s

Table 1 Sensor Performance Specifications

Figure 1 Rel. Humidity, Temperature and Dewpoint accuracies

2 Interface Specifications

Figure 2 Typical application circuit

2.1 Power Pins

The SHTxx requires a voltage supply between 2.4 and 5.5 V. **After powerup the device needs 11ms to reach its "sleep" state. No commands should be sent before that time.**

Power supply pins (VDD, GND) may be decoupled with a 100 nF capacitor.

2.2 Serial Interface (Bidirectional 2-wire)

The serial interface of the SHTxx is optimized for sensor readout and power consumption and is not compatible with I²C interfaces, see FAQ for details.

2.2.1 *Serial clock input (SCK)*

The SCK is used to synchronize the communication between a microcontroller and the SHTxx. Since the interface consists of fully static logic there is no minimum SCK frequency.

2.2.2 *Serial data (DATA)*

The DATA tristate pin is used to transfer data in and out of the device. DATA **changes after the falling edge** and is **valid on the rising edge** of the serial clock SCK. During transmission the DATA line must remain stable while SCK is high. To avoid signal contention the microcontroller should only drive DATA low. An external pull-up resistor (e.g. 10 kΩ) is required to pull the signal high. (See Figure 2) Pull-up resistors are often included in I/O circuits of microcontrollers.

See Table 5 for detailed IO characteristics

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(1) The default measurement resolution of 14bit (temp.) and 12bit (humidity) can be reduced to 12 and 8 bit through the status register. (2) Effective number of bits is 11bit.

(3) Each SHTxx is tested to be fully within accuracy specifications at 25°C (77°F) and 3.3V.

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Relative Humidity calibration example

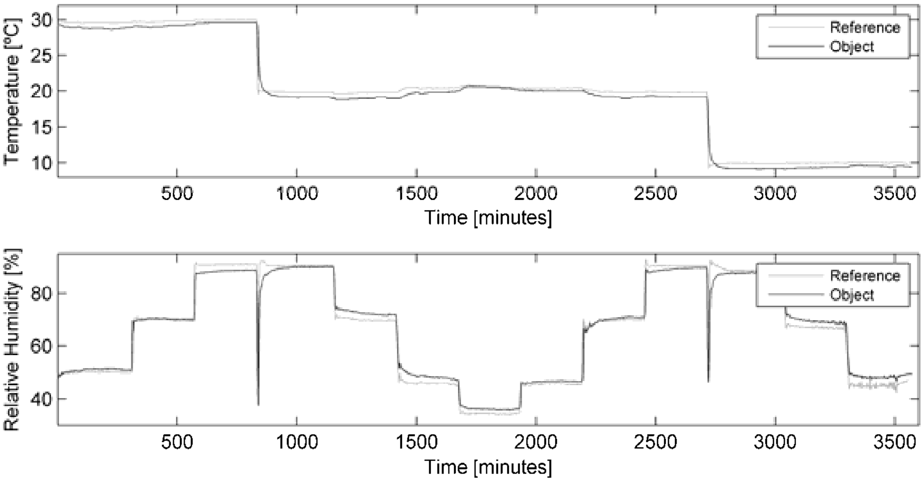

Figure A1: Relative Humidity trajectory.

Table A1: Relative Humidity calibration: average value per set point (most constant period per set point)

RHreference	RHobject	RHcorrection
50.244	51.353	-1.11
70.343	69.944	0.398
90.929	88.543	2.39
90.514	89.938	0.576
69.658	71.922	-2.26
45.913	48.142	-2.23
34.404	36.016	-1.61
45.729	46.738	-1.01
69.97	70.879	-0.909
90.485	89.623	0.862
88.551	87.821	0.73
66.843	68.99	-2.15
45.083	48.146	-3.06

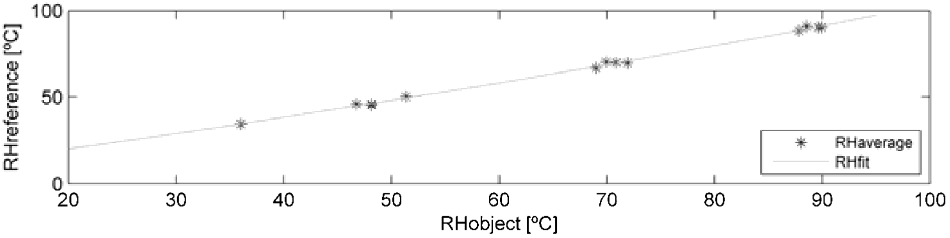

Figure A2: Relative Humidity calibration correction function.

RHfit = B2 * $(RHobject)^2$ + B1 * RHobject + B0

B2 = 0.0020393;	B1 = 0.79398;	B0 = 3.2653
sB2 = 0.00014159;	sB1 = 0.018708	sB0 = 0.58073
2*sRHfit = 1.8832	R^2 = 0.99765	number of points per average = 49

Temperature calibration example

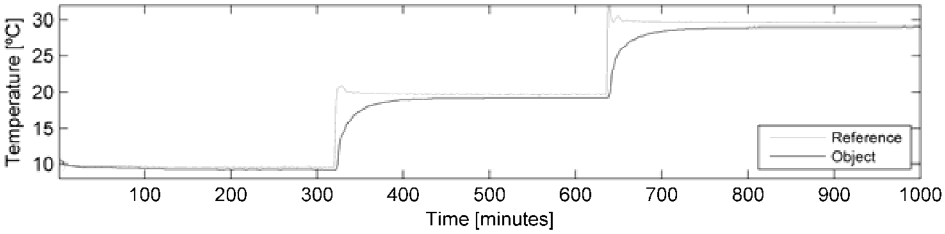

Figure A3: Temperature calibration trajectory.

Table A2: Temperature calibration: average value per set point (most constant period per set point)

Treference	Tobject	Tcorrection
9.7329	9.2865	0.446
19.756	19.169	0.588
29.707	28.955	0.752

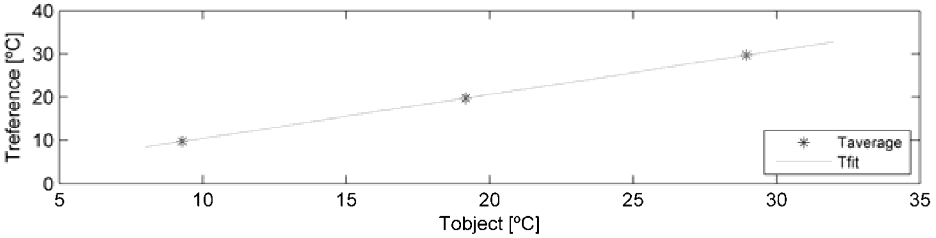

Figure A4: Temperature calibration correction function.

Tfit = B2 * $(Tobject)^2$ + B1 * Tobject + B0

B2 = 0.00011652;	B1 = 1.011;	B0 = 0.33391
sB2 = 7.5306e-5;	sB1 = 0.0029102	sB0 = 0.02433
2*sTfit = 0.11835	R^2 = 0.99995	number of points per average = 98

Appendix B: Room condition results

Table B1: Results for average room conditions: Position & type, mathematical and climate class properties.

Position		Types					Statistical parameters												General risk assessment					
Museum	Room	QoE	LoC	Building Type	System Type	Position Type	T annual mean	T winter drop	T summer rise	dT hour	dT day	dT week	RH annual mean	R winter drop	R summer rise	dRH hour	dRH day	dRH week	Class AA	Class As	Class A	Class B	Class C	Class D
M01	R01	1	3	1	3	1	19.51	2.5	3.4	0.3	1.8	4.1	55.5	4.8	4.7	0.7	5.2	12.4	56	72.9	78.6	98.4	100	100
M01	R02	1	3	1	3	1	20.34	1.8	3.1	0.2	1.7	3.9	52.4	5.8	5.4	0.7	5.1	11.5	50.2	74.4	80.4	98.4	100	100
M01	R03	1	3	1	3	1	20	2.2	3.1	0.2	1.9	4.3	53.7	5.6	4.7	0.8	5.3	12.3	58.8	74.9	81.1	98.7	100	100
M01	R04	1	3	1	3	1	20.14	2	3.5	0.2	1.8	4.1	53.1	5.6	5.3	0.7	5.1	11.6	57.3	74	79.9	97.9	100	100
M01	R05	1	2	1	2	1	20.83	2.5	3.4	0.1	1.5	3.3	49.5	9.2	5.5	0.7	7.2	17	44.2	60.7	71	96.9	100	100
M01	R06	1	2	1	2	4	21.56	2.4	2.6	0.3	3	5.7	46.5	9.8	6.9	1	9.8	20.5	32.3	50.8	60.7	94.7	100	100
M01	R07	1	3	1	3	1	20.68	1.9	2.9	0.1	1.5	3.8	51.7	6	4.3	0.7	5.4	12.7	53.8	73	82.2	98.7	100	100
M01	R08	1	2	1	2	1	20.51	1.5	2.7	0.1	1.3	3.4	49.7	9.7	7	0.7	6.7	15.8	35.3	55.5	65.3	94.2	100	100
M02	R01	1	1	1	1	1	14.45	6.8	7.2	0.1	0.7	2.5	54.9	2.9	5.7	0.7	5.6	13.1	47.2	58.8	72.5	97.9	100	100
M02	R02	1	1	1	1	1	15.34	6.6	6.8	0.2	1.1	2.7	52.3	2.1	5	0.5	4	9.8	59.2	70.1	78.4	99.7	100	100
M02	R03	1	1	1	1	1	13.87	5.5	6.1	0.2	1	2.7	60.6	2.8	2.6	0.5	4.5	12.5	60	65.6	80.2	96.1	100	100
M02	R04	1	2	1	2	1	18.32	2.3	3.5	0.3	2	4.9	48.5	11	9.9	0.6	6.1	17.4	18.6	41.1	43.1	79.3	99.6	100
M02	R05	1	1	1	1	1	13.73	5.7	6.2	0.3	1	2.1	64.6	2.2	2.7	0.6	5.5	15.7	53.1	55.4	80.8	92.3	96.4	96.4
M02	R06	1	1	1	1	1	13.34	5.8	6.4	0.3	0.9	2	67.1	2.9	5.3	0.5	5.3	16	49.7	53.3	75.1	87.6	88.1	88.1
M02	R07	1	1	1	1	1	14.38	6.3	6.7	0.4	1.7	3.2	61.7	4.6	6.4	0.7	5.1	12.6	51.2	61.5	75.6	97.5	98.9	98.9
M02	R08	1	1	1	1	1	14.26	7.3	6.2	0.3	1.3	2.7	64.6	3	7.6	0.5	5	13.8	39.7	53.5	68.2	93.8	94.4	94.4
M02	R09	1	1	1	1	1	14.56	5.6	6.3	0.1	0.8	2.4	62.6	4.4	4.1	0.5	5.1	14.8	50.1	57.3	74.5	92.9	97.2	97.2
M02	R10	1	1	1	1	1	13.83	6.6	7.1	0.1	0.9	2.5	63.5	3.6	5.7	0.5	4.7	12.1	48.9	58.2	71.7	95.9	96.4	96.4
M02	R11	1	2	1	2	4	14.96	6.6	6.9	0.2	1.2	2.8	54.1	2.1	5.1	0.4	3.5	8.7	61	72.2	78.5	99.8	100	100
M02	R12	1	1	1	1	1	12.69	4.6	5.1	0.3	0.8	1.6	71.9	3.7	6.8	0.7	6.7	18.2	45.3	54.8	79.7	89	63.5	63.5
M02	R13	1	1	1	1	5	11.84	5.2	5.5	0.1	0.5	1.6	72.9	2.9	3.6	0.9	7.1	17.2	53.2	57.7	82.6	93.8	62	62
M02	R14	1	1	1	1	1	12.85	4.9	5	0.1	0.4	1.2	73.3	4.5	6.8	0.7	6.4	17.7	47.1	56.6	79.6	89.2	59.5	59.5
M02	R15	1	1	1	1	1	13.46	4.8	5.1	0.3	1.1	2.3	69.1	4.1	7.5	0.6	6.3	17.2	42.6	53.9	76.7	89.5	77.5	77.5
M02	R16	1	1	1	2	1	16.65	4.9	6.1	0.2	1.7	4	49.6	3.5	2.6	0.6	5.8	15.8	42.7	48.4	71.1	90.3	100	100
M02	R17	1	2	1	2	1	17.28	1.1	1.8	0.8	3.8	5.9	52	13.9	16.4	2.6	13.1	25.3	16.7	34.7	33.5	73.9	97.4	98
M02	R18	1	1	1	1	1	16.04	4.3	5	0.1	1.2	3.2	55.6	7.2	5.3	0.6	5.8	16.1	41.3	50	63.7	84.8	99.8	99.8
M02	R19	1	1	1	1	1	12.41	5.1	5.6	0.3	1	2.1	73.4	2.5	5	0.7	6.7	17.9	48	55.1	81.1	90	57.1	57.1
M02	R20	1	1	1	1	5	12.08	5.8	6.3	0.1	0.7	2.4	73.3	2.4	3.6	0.6	6.3	17.1	46.2	50.9	74.2	89.6	58.8	58.8
M02	R21	1	1	1	1	5	13.55	7.3	8.1	0.4	4.3	9.1	65.6	11.5	11.7	1.5	15.1	30.2	12.5	26.9	29.4	75	77.1	77.1
M02	R22	1	1	1	1	5	14.63	5.7	6.5	0.2	1.3	3.4	61.1	5.1	4.8	0.5	5.5	14.8	46.5	57.3	71.5	92.9	98.1	98.1
M04	R01	2	2	1	2	3	20.83	1.5	2	0	0.4	1.2	34.2	2.7	3.8	0.4	5.5	11.7	79	88.6	95.2	95.3	100	100
M04	R02	2	2	1	2	3	18.54	3.9	3.8	0.4	4.8	8.5	50.2	7.6	7.1	1	10.2	21.7	25.6	39.2	47	85.2	99.9	100
M04	R03	2	2	1	2	1	20.49	1.5	1.9	0.4	2.5	3.7	47.3	12.5	11.2	1.1	8.5	19.5	27.1	55.3	54.1	92.5	99.3	100
M04	R04	2	2	1	2	1	18.2	3.6	3.9	0.3	2.2	4.3	57.5	5.1	6.4	0.9	7.4	15.7	47.7	59.3	72.6	97.6	100	100
M04	R05	2	2	1	2	1	19.79	2.6	3.2	0.4	3.3	5.3	52	6.5	7.6	1.1	9.2	17.7	40.6	55.3	66	96.5	100	100

Table B1 (continuation)

Position		Types					Statistical parameters												General risk assessment					
Museum	Room	QoE	LoC	Building Type	System Type	Position Type	T annual mean	T winter drop	T summer rise	dT hour	dT day	dT week	RH annual mean	R winter drop	R summer rise	dRH hour	dRH day	dRH week	Class AA	Class As	Class A	Class B	Class C	Class D
M04	R06	2	3	1	3	1	21.07	2.2	2.9	0.3	2.4	4	50.5	4.4	4.1	0.8	6.6	12.5	61.9	75.7	83.9	98.9	100	100
M04	R07	2	3	1	3	1	21.77	1.7	2.2	0.2	2.3	3.7	47.9	6.5	6	0.8	6.5	12.7	51.3	74	81	98.7	100	100
M04	R08	2	3	1	3	2	21.12	2.7	2.9	0.3	2.8	4.8	54.3	8.2	6.9	0.4	3.5	5.8	30.1	85.4	84.9	99.8	100	100
M04	R09	2	3	1	3	2	21.21	1.8	2.4	0.2	2	3.5	48.4	9.4	7.5	0.4	5	11	38.5	73.3	72.9	99.1	100	100
M04	R10	2	2	1	2	4	17.97	6.4	4.1	0.3	4.1	7.7	57	15	6.2	0.8	8.2	17.1	25.6	47.6	55.6	89.2	100	100
M05	R01	1	2	1	2	1	23.03	2.1	1.2	0.3	2.9	5	38.6	13.1	15.1	1.4	11.4	23.4	18.6	50.4	44.9	88.4	85.9	100
M05	R02	1	1	1	1	1	15.32	4.2	4.7	0.1	0.8	2.2	62.3	3.1	4.5	0.6	5.4	14	68.4	78	92.8	98.5	99.8	99.8
M05	R03	1	1	1	1	1	13.68	6.5	6.8	0	0.5	2.1	65.9	3.6	7.8	0.4	4	11.3	47.2	63	71.8	97.1	92.4	92.4
M05	R04	1	1	1	1	1	13.13	5.3	4.9	0.2	1.8	3.8	72.4	3.8	4.7	1.1	9.8	22.8	46	49.8	77.4	88.1	60	60
M05	R05	1	2	1	2	1	21.8	3.2	1.7	0.1	1.4	3.5	41.6	9.4	13.1	0.6	7	16.6	26.8	54.5	53.9	94.1	98.4	100
M05	R06	1	1	1	1	1	14.92	6	6.2	0.2	1.5	3.2	63.5	2.6	5.2	0.5	4.7	12.8	59.6	67.7	81.2	97.6	98.5	98.5
M05	R07	1	2	1	2	1	17.92	2	2.1	0.2	1.6	2.8	56.2	16.4	12.4	1	9.5	22.7	29.4	51.5	54.4	85.4	97.3	97.3
M05	R08	1	1	1	1	1	13.99	7.5	7.7	0.3	3.7	7.7	67.7	10.1	13.8	1.1	12	25	15.7	31.5	32.1	84.2	70.6	70.6
M06	R01	1	2	2	6	1	20.08	1.9	1.7	0.2	1.5	3.5	45.5	14.4	17.2	1.1	10.1	23.6	15.4	34.9	35	73.9	92.3	99.7
M06	R02	1	2	2	6	1	19.33	3.4	2.5	0.2	1.9	4.5	45.3	12.7	15.1	0.7	7.9	19.3	20.7	33.5	37.7	82.1	96.4	100
M06	R03	1	2	2	6	1	19.97	2.3	1.7	0.3	3	5.8	44.6	13.1	16.5	1	10	23.4	16.6	34.4	35.2	75.6	92.2	100
M06	R04	1	2	2	6	1	20.45	2.2	1.2	0.3	2.9	6.2	42.8	14.4	17.5	0.9	10.7	24.9	10.7	25.2	24.9	65.9	86	99.9
M06	R05	1	2	2	6	1	20.68	3.8	2	0.3	2.6	5.7	42.5	14.9	15.9	0.7	8	19.9	15.6	30.1	32	75.3	88.3	100
M06	R06	1	2	2	6	1	20.49	4.6	1.1	0.3	2.6	6	41.6	12.4	16.8	0.7	8.4	21.4	10.9	28.2	25.5	69.8	85.4	100
M06	R07	1	2	2	6	1	20.28	2.6	1.9	0.3	2.4	4.8	45.1	13.3	16.2	1.1	10.4	24.5	14.7	32	32.7	71.6	91.9	100
M06	R08	1	2	2	6	1	20.33	2.2	1.3	0.4	2.7	5.5	44.9	18	16.3	0.9	9.4	22.4	13.3	33.4	30.3	76.2	90.7	99.8
M06	R09	1	2	2	6	1	20.96	1.3	1.7	0.2	2.1	4.5	44.5	15.8	19.5	0.7	7.6	19.3	9	28.8	22.6	66.5	87.7	99.9
M06	R10	1	2	2	6	1	18.93	5.6	4	0.5	4.8	9.4	48.2	11.8	14.4	1.5	15.8	30.8	21.4	25.6	33.8	67	95.7	98.6
M06	R11	1	2	2	6	1	20.75	2.1	1.4	0.2	1.6	3.5	43.3	14.1	17.4	0.9	8.1	20.2	13.7	36.3	32.3	76.5	88.7	100
M06	R12	1	2	2	6	1	20.26	1.6	1.3	0.2	1.8	4.3	45.3	15.1	18.6	0.7	7.5	19.1	10	31.2	26.9	69.9	90.4	100
M06	R13	1	2	2	6	1	21.49	3	1.2	0.3	2.8	5.8	40.9	13.4	17.4	0.7	8.5	20.8	12.5	31	29.2	72.5	84.3	100
M07	R01	2	4	1	10	4	19.21	3.1	3.8	0.3	3.5	5.7	47.1	3.8	5.9	0.8	9.8	20.3	39	49.4	68.9	86.5	100	100
M07	R02	2	4	1	10	3	18.57	0.3	0.3	0.1	0.8	1.6	49.2	11.7	4.5	1.4	6.1	12.1	73.9	83.7	90.9	96.2	99.9	100
M07	R03	2	4	1	10	4	19.88	1.1	1.4	0.1	1.3	2.2	45.4	8.5	4.6	0.7	5.4	11.9	65.9	86.6	93.5	98.3	100	100
M07	R04	2	4	1	10	2	19.24	1.9	1.3	0.1	1.6	2.5	48.3	7.3	2.2	0.1	1.6	3	88.2	98	97.9	100	100	100
M07	R05	2	4	1	10	2	20.2	1.9	2	0.1	1.1	2	45	6.8	4.5	0.5	2.4	4.3	85.7	97.7	98.6	100	100	100
M07	R06	2	4	1	10	1	19.52	2.2	1.5	0.2	2.4	3.6	46	6.2	3.6	1	7.5	14.8	72.4	79.8	91	95.8	100	100
M07	R07	2	4	1	10	6	16.83	1.1	1.5	0.3	1.8	3.3	56	14.9	8.7	4.5	14.4	24.1	38.3	65.4	72.7	89.8	99.9	100
M07	R08	2	4	1	10	1	20.32	1.1	1.2	0.2	2	2.9	43.4	9.4	4	0.8	6	11.6	71	82	90.4	98	99.2	100
M07	R09	2	4	1	10	1	20.12	0.9	1.3	0.2	2.1	2.8	45.7	9	3.7	0.7	5.7	11.3	75.9	86	92.4	98.2	100	100
M07	R10	2	4	1	10	1	20.63	0.9	1.4	0.2	2.5	3.5	44.1	9.2	3.5	1.1	7.3	13.3	71.8	81.8	89.6	97.9	99.6	100
M07	R11	2	4	1	10	1	19.51	1	1.2	0.2	2.1	4	47.3	8.4	3.7	1.1	8.2	16.4	73.9	79.5	90.4	95.5	99.8	100
M07	R12	2	4	1	10	6	16.71	1.5	1.4	0.4	1.8	3.3	56.8	16.7	10.8	4.1	13.4	22.7	34	63.8	64.7	88.4	99.8	99.9
M07	R13	2	4	1	10	1	19.54	0.9	1	0.2	1.6	3.2	46.9	8.9	4	1.2	7.8	15.7	75.1	82	91.9	96.1	99.8	100
M07	R14	2	4	1	10	1	19.88	1.5	1.8	0.2	2.7	4.1	45.8	8.4	4.4	1.1	8.7	17.2	65.9	75.9	86.6	96.2	99.6	100
M07	R15	2	4	1	10	1	20.19	1.1	1.3	0.2	2.2	3.2	45.1	11	3.6	0.9	7.2	13.3	73	82.8	88.7	97.1	99.1	100
M07	R16	2	4	1	10	1	20.04	0.9	1.2	0.1	1.4	2.4	45.5	9.1	3	0.7	5.7	11.5	83.3	87.4	92.9	98	99.9	100
M07	R17	2	4	1	10	1	20.37	1.2	1.8	0.2	2.3	3.5	43.5	8.6	2.6	1.1	6.3	11.8	73.2	81.4	88.5	97.7	99.7	100
M07	R18	2	4	1	10	1	21.9	1.7	1.8	0.3	2.6	4.4	40.6	9.6	2.4	1.1	6.8	12.8	68.1	74.4	82.9	97.4	97.6	100
M07	R19	2	4	1	10	1	21.03	1.1	1.8	0.2	2.5	3.9	41.7	8.2	2.5	1	6.1	11.5	74.6	81.3	88	98	99.3	100
M08	R01	1	2	1	2	1	20.43	5.2	3.5	0.2	1.9	4.2	47.5	7.9	5.7	0.6	6.6	16.1	39.7	62	74.6	96.8	100	100
M08	R02	1	1	1	1	1	16.54	6.5	5.2	0.1	1.7	4.1	59.2	5.4	5.7	0.4	5.5	14.7	43.3	50.6	70.5	94.9	99.2	99.2

Table B1 (continuation)

Position		Types					Statistical parameters												General risk assessment					
Museum	Room	QoE	LoC	Building Type	System Type	Position Type	T annual mean	T winter drop	T summer rise	dT hour	dT day	dT week	RH annual mean	R winter drop	R summer rise	dRH hour	dRH day	dRH week	Class AA	Class As	Class A	Class B	Class C	Class D
M08	R03	1	1	1	1	1	15.53	7.7	6.4	0.2	3	6.4	62.8	6.8	10.9	0.7	8.5	21.6	27.7	38.3	52.3	88.6	91.3	91.3
M08	R04	1	1	1	1	1	15.4	7.6	7.1	0.1	1.2	3.1	63.4	7.1	10.8	0.5	5.5	15.1	27.8	53.3	60.5	96.3	92.2	92.2
M08	R05	1	1	1	1	1	14.94	8	7.4	0.2	2.2	4.9	64	8.2	15.1	0.6	6.3	16.1	23.9	40.4	43.7	91.6	85	85
M08	R06	1	1	1	1	1	15.87	8.2	6.8	0.2	2.2	4.9	61.6	7.6	15.4	0.6	6	15.5	26.8	42.7	47.5	92.8	90	90
M08	R07	1	1	1	1	1	15.4	8.8	7.7	0.2	2.6	5.6	63	10.4	16	0.6	6.4	15.4	17.1	39.7	39.6	93.1	86.1	86.1
M08	R08	1	1	1	1	1	14.96	8.7	7.6	0.2	2.2	4.9	64.6	9.4	14.1	0.4	4.7	11.9	19.6	46.9	44.5	96.8	83.9	83.9
M08	R09	1	1	1	1	1	14.39	8.2	7.1	0.1	1	3.1	67.3	7.9	12.2	0.3	4.2	11.9	25	57.1	56.4	97.9	79.9	79.9
M08	R10	1	1	1	1	1	14.51	6.8	7.1	0.1	1.4	2.9	68.4	5.7	13.5	0.4	4.7	12.9	35.4	54.3	61.3	95.4	82.5	82.5
M08	R11	1	1	1	1	1	15.17	8	7.3	0.2	2.5	4.5	63.3	6.9	14.7	0.6	6	12.9	28.1	49	53	97.3	91.5	91.5
M08	R12	1	1	1	1	1	12.21	6.9	7	0.1	1	3	76.8	5.7	8.3	0.5	4.9	12.4	35.7	57.5	63.3	96.9	39.6	39.6
M08	R13	1	1	1	1	1	13.93	7.5	6.4	0.2	1.9	4.2	67.6	4.8	10.9	0.7	7.5	18.9	33.6	42.1	57.7	89.5	83.6	83.6
M08	R14	1	1	1	1	1	14.03	6.8	6.8	0.1	1.7	3.4	66.9	4.3	10.3	0.6	6.8	17.4	37.6	47.7	64.2	93.7	87.3	87.3
M08	R15	1	1	1	1	1	14.1	7.2	6.4	0.1	1.5	3.5	68.3	4.3	10.3	0.6	6.4	16.9	36.7	47.9	64	94	82.4	82.4
M08	R16	1	1	1	1	1	15.57	6	6.3	0.1	1.1	2.4	64.5	3.4	8.8	0.4	4.8	14	51.4	60.3	81.3	96.5	96.8	96.8
M08	R17	1	1	1	1	1	16.85	6.3	5.3	0.3	3.1	6.1	59.5	2.9	8	0.8	9	21.4	39.7	44.6	69.9	89	98.6	98.6
M09	R01	1	2	1	2	1	20.41	1.8	0.7	0.2	1.9	5.2	48.1	13.5	16.5	0.6	5.2	14.8	14.3	44.9	32.9	89.2	99.9	99.9
M09	R02	1	1	1	1	1	15.73	5.3	5.6	0.2	2	5.9	63.6	6	4.6	1.2	11.3	27.2	34.6	40.3	61.6	82.4	93.2	93.2
M09	R03	1	2	1	2	1	20.47	2.2	2.1	0.4	3.3	6.8	47.6	11.2	13.5	0.9	6.4	14.4	17	43.1	34	93.1	100	100
M09	R04	1	1	1	1	1	16.41	6.3	6.2	0.2	2.9	7.4	60.4	7.7	7.4	0.7	7.1	17.9	31.7	48.4	55.7	92.8	99.2	99.2
M09	R05	1	2	1	2	1	18.42	5	4.3	0.1	1.7	5	53.3	7.8	8.4	0.3	3.6	10.8	26.2	53.1	53.4	89.7	100	100
M09	R06	1	1	1	1	1	13.91	6.5	6.5	0.1	1.7	5.2	71.1	8.9	9.6	0.3	2.9	8.7	21.8	47.2	46	86	60.1	60.1
M09	R07	1	1	1	1	3	14.27	6.6	6.7	0.1	1.8	5	67.5	9.4	9	0.4	3.7	9.7	27.6	56.8	53.5	95.5	83.1	83.1
M09	R08	1	1	1	1	3	14.6	8.3	7.3	0.2	2.8	6.7	67.6	12.2	11.1	0.6	7.4	15.7	20.8	45.6	39.1	90.8	74.7	74.7
M09	R09	1	1	1	1	4	13.43	6.8	7.5	0.2	2.1	5.8	73.6	12.3	11.4	0.5	5	12	21.8	48.4	42.3	92	51.9	51.9
M09	R10	1	1	1	1	4	14.81	8.5	8.2	0.5	6.2	11	67.5	15.3	14.1	1	10.9	17.6	12.1	38.4	27.2	83.3	64.9	64.9
M10	R01	2	4	2	10	3	19.72	2.1	1.7	0.2	1.3	2.6	52.9	5	6.5	0.5	5.1	12.9	55.6	68.7	85.5	96.7	100	100
M10	R02	2	4	2	10	2	17.49	1.7	1.6	0.1	0.8	1.5	61.5	4.6	5.7	0.4	4.5	11.3	68	84.7	95.1	98.6	100	100
M10	R03	2	4	2	10	1	19.1	0.8	1.1	0.1	1.2	2.2	56.4	12.1	12.8	1.3	10.2	21.5	22.5	63.1	55.4	88.6	95	95.2
M10	R04	2	4	2	10	1	18.51	1.7	1.8	0.2	2.5	3.4	56	4.2	5.8	1.1	10.9	21.4	57.7	63.2	82.7	91.5	99.8	99.8
M10	R05	2	4	2	10	1	18.98	1.3	1.4	0.1	1.7	2.7	55.7	6	6.9	1	9.2	20	52.7	65.3	83	91.3	99.6	99.6
M10	R06	2	4	2	10	1	18.18	1.3	1.5	0.1	1.8	2.9	58.7	6.4	6.9	1	9.5	20.4	52.1	62.8	81.2	90.7	99	99
M10	R07	2	4	2	10	1	19.12	3.2	2.2	0.1	1.3	2.6	55.7	8.8	6.1	1.1	9.6	21.3	42.2	57.1	68.3	88.8	99.9	99.9
M10	R08	2	4	2	10	1	18.45	1.4	0.9	0.1	1.5	2.6	58.5	11.7	9.5	0.9	8.9	19.8	36.1	66.3	63.7	92.4	97.7	97.7
M10	R09	2	4	2	10	1	20.29	1.3	1.1	0.2	1.5	2.3	50.5	5.4	8	0.8	8	17.4	52.1	69.7	82	93.9	99.9	100
M10	R10	2	4	2	10	1	19.31	1.3	1.6	0.2	2	3.8	54	6.1	6.7	0.8	7.9	16.9	54.8	69.2	81.6	94.7	100	100
M10	R11	2	4	2	10	1	18.18	1.5	1.7	0.1	1.4	2.3	58.4	4.5	6.8	0.9	9.4	20.7	53.7	62.9	82.4	89.8	99	99
M10	R12	2	4	2	10	1	17.84	1.4	1.6	0.1	0.6	1.6	60.6	5.9	6.5	1.5	11	23	51.3	55.1	77.2	88.1	97.4	97.4
M11	R01	2	2	1	10	6	25.43	7	0.9	0.3	2.9	5.5	21.2	6.2	23.1	1.7	9	17.9	43.9	77.8	84.6	93	29.3	100
M11	R02	2	2	1	10	1	20.55	1.1	1.3	0.1	0.6	1.4	45.1	16.1	10.7	0.7	6.3	14.2	23	60.1	54.9	91.2	96.9	100
M11	R03	2	2	1	10	6	19.16	2.4	1.9	0.4	3.7	7.3	53.8	17.8	14.6	2.1	14.4	31.2	18	35.7	34.6	74.6	95	95.3
M11	R04	2	2	1	10	4	20.73	1.2	1.6	0.1	1.1	1.7	47.6	17.4	12.3	0.8	5.8	14.2	28.9	58.3	48.6	90.3	96.6	100
M11	R05	2	2	1	10	1	19.5	1.3	1.6	0.2	2.1	3.3	45.9	16.7	9.2	0.8	7.7	15.1	24.6	53.3	49.6	91.9	96.3	100
M11	R06	2	2	1	10	1	20.01	1.1	1.8	0.2	0.9	1.7	45	15.7	8.2	0.5	4.8	11.5	32.5	63.3	64.3	95	95.8	100
M11	R07	2	2	1	10	1	18.81	3.2	2.8	0.3	3.1	5.2	46.4	12.5	7.4	0.9	8.2	17.2	31.1	53.9	61.7	93.4	99.4	100
M11	R08	2	2	1	10	1	19.5	1.2	1.5	0.3	1.7	2.9	45.9	15.4	9.7	0.5	3.9	9.2	34.5	74.4	64.8	97.7	99.3	100
M11	R09	2	2	1	10	1	19.13	2.7	2.5	0.2	2	3.7	46.6	13.6	8.4	0.7	5.7	12.4	25.8	62.7	65.2	98.4	99.9	100
M11	R10	2	2	1	10	2	19.09	2.9	2.7	0.2	1.8	3.5	45.4	11.6	7.2	0.3	2.1	5.6	39	82.5	75	100	100	100

Table B1 (continuation)

Position		Types					Statistical parameters												General risk assessment					
Museum	Room	QoE	LoC	Building Type	System Type	Position Type	T annual mean	T winter drop	T summer rise	dT hour	dT day	dT week	RH annual mean	R winter drop	R summer rise	dRH hour	dRH day	dRH week	Class AA	Class As	Class A	Class B	Class C	Class D
M11	R11	2	2	1	10	1	20.48	0.7	0.3	0.3	2.5	4.4	41.6	18.7	16.9	1	7.5	15.3	25.6	46.2	36.8	84	86.1	100
M11	R12	2	2	1	10	2	19.74	0.7	0.7	0.2	1.9	3.7	44.5	16.4	12.6	0.3	2.1	4.8	31.6	76.6	52.6	99.8	99	100
M11	R13	2	2	1	10	2	20.01	0.5	0.5	0.2	1.9	3.7	43.6	16.4	13.1	0.3	1.5	3.6	29.3	76.8	51.1	99.9	98.4	100
M11	R14	2	2	1	10	1	20.38	1	1.1	0.4	3.3	6.1	43.7	16.7	14.5	1.1	9.9	20.5	22.9	41.3	37	85.4	92.2	100
M11	R15	2	2	1	10	3	21.9	1.1	1.8	0.2	1.5	3.7	39.3	19.9	15.5	0.7	5.4	11.3	20.2	47.8	31.2	88.9	75.1	100
M12	R01	3	4	1	12	1	20.03	0.7	0.9	0.1	0.5	1.2	54.6	1.8	1.4	2.1	8.3	14.2	95.5	96.6	99.2	99.5	100	100
M12	R02	3	4	1	12	1	20.24	1	1.1	0.1	0.7	1.5	54.6	3.4	2	1.7	6.1	10.6	95.1	96.7	98.2	99.3	100	100
M12	R03	3	4	1	12	4	23.49	1.9	1.7	0.3	1.6	2.4	44.2	6	4.6	1.5	8.9	14.9	69	86.1	94.8	99.6	100	100
M12	R04	3	4	1	12	4	21.67	2.2	2.1	0.2	2.1	2.8	48.6	5.6	3	0.9	6.9	13.4	75.9	87.2	96.6	99.1	100	100
M12	R05	3	4	1	12	4	19.06	2.5	2.4	0.2	2.3	3.4	57.5	4.4	2.5	0.6	5.7	11	74.9	83.2	93.7	100	100	100
M12	R06	3	4	1	12	4	20.93	1.2	2	0.2	1.7	3	49.3	6	3.2	0.6	5.3	10.6	74	90.4	95.8	99.8	100	100
M12	R07	3	4	1	12	4	20.99	1.9	1.9	0.2	1.8	2.4	50.6	6.4	3.5	0.8	6.3	11.6	73.5	88.4	96.3	99.5	100	100
M12	R08	3	4	1	12	3	20.86	1	1.2	0.1	0.9	1.5	49.6	6.3	4.9	0.4	4.1	7.8	69.5	95	96.4	100	100	100
M12	R09	3	4	1	12	2	20.26	1.6	1.1	0.1	0.9	1.5	57.3	0.9	1.2	0.1	1	1.4	99.6	99.6	99.6	100	100	100
M12	R10	3	4	1	12	4	19.28	3.8	3	0.2	1.4	2.5	55.7	3.9	6.4	0.5	4.6	8.1	78.3	96.2	97	100	100	100
M12	R11	3	4	1	12	4	19.77	4.2	3.1	0.3	3.4	6.3	55.4	4.5	8.1	0.8	7.5	14.3	64.4	92.1	90.6	99.5	100	100
M12	R12	3	4	1	12	4	19.96	2.6	2.2	0.2	2.3	4.7	55.9	2.8	4	0.7	6.7	13	84	95.2	96.5	99.4	100	100
M12	R13	3	4	1	12	4	19.24	3.1	2.7	0.2	1.5	2.6	56.5	4.3	5.5	0.6	5.4	9.2	76.9	96.7	98.4	100	100	100
M12	R14	3	4	1	12	1	20.46	1.7	1.2	0.1	0.7	1.3	52.7	1.1	1.9	0.5	3.2	6.3	97.7	98.6	99.9	100	100	100
M12	R15	3	4	1	12	1	19.22	2.3	2	0.1	1	1.7	56	1.6	2.3	0.3	2.9	5.6	99	99.2	100	100	100	100
M12	R16	3	4	1	12	1	20.15	1.5	1.4	0.2	1.1	1.8	53	1	1.6	0.4	3.6	6.7	97.9	98.6	99.9	100	100	100
M12	R17	3	4	1	12	1	19.7	2.3	2	0.2	1.1	1.8	55.3	1.6	2.6	0.5	3.6	6.2	98.4	99.3	100	100	100	100
M12	R18	3	4	1	12	1	19.59	1.8	1.6	0.1	1	1.8	56.2	0.7	0.8	0.5	3.7	6.4	99.1	99	100	100	100	100
M12	R19	3	4	1	12	1	19.9	2.4	1.9	0.2	1.3	2.2	55.2	1.8	3	0.5	3.3	5.6	98.8	99.1	99.9	100	100	100
M12	R20	3	4	1	12	1	20.45	1.5	1.1	0.2	1.3	2.1	52.9	1.3	1.6	0.4	3	5.5	98	98.6	99.9	100	100	100
M12	R21	3	4	1	12	1	19.72	2.4	1.8	0.2	1.4	2.2	55.7	2.3	2.9	0.4	3.1	5.5	98	98.9	100	100	100	100
M12	R22	3	4	1	12	1	19.92	1.5	1.3	0.2	1.2	2	55.3	0.5	0.8	0.5	3.7	6.3	98.7	98.8	100	100	100	100
M12	R23	3	4	1	12	1	20.59	0.8	0.8	0.1	0.8	1.3	53	2.5	2.2	0.3	2.8	5	97.6	98.9	100	100	100	100
M12	R24	3	4	1	12	1	19.69	1.1	1.1	0.2	1.2	1.8	56	1.2	0.8	0.5	4.2	6.7	98.4	98.5	100	100	100	100
M12	R25	3	4	1	12	1	19.9	1	1	0.2	1.1	1.7	55.6	1.8	1.1	0.4	3.4	5.8	98.5	98.8	100	100	100	100
M12	R26	3	4	1	12	1	19.76	1.1	1.1	0.2	1.4	2	55.3	1.9	1.5	0.6	5.4	8.8	97.2	97.6	99.9	100	100	100
M12	R27	3	4	1	12	1	20.22	1	0.9	0.2	1.1	1.6	52.9	2.3	2.4	0.5	4	7.1	97.3	98.6	99.8	100	100	100
M12	R28	3	4	1	12	1	20.13	1.3	1.3	0.2	1.1	1.8	53.7	0.8	0.9	0.5	3.8	6.7	98.8	99	99.9	100	100	100
M12	R29	3	4	1	12	1	20.32	0.8	0.8	0.3	2.7	3.5	54.3	3.1	2.8	1	8.8	12.7	86	92.4	96	98.9	100	100
M13	R01	1	3	1	3	2	21.3	2	1.7	0.1	0.6	1.6	46.2	7.3	6.6	0.1	1	3.6	35	88.4	90.3	99.8	100	100
M13	R02	1	3	1	3	2	20.98	2.1	1.7	0.1	0.9	2	46.3	9.9	7.2	0.1	0.7	2.8	26.4	98.4	87.7	99.8	100	100
M13	R03	1	3	1	3	1	20.31	1.6	1.9	0.1	1.3	2.4	49.5	10.6	7.4	0.4	4.3	11.9	31	76.2	75.9	95.6	100	100
M13	R04	1	3	1	3	2	21.06	2.2	1.9	0.1	1.1	2.2	44.8	8.4	6.2	0.1	1.2	3.5	39.7	96.7	90.9	100	100	100
M13	R05	1	3	1	3	2	20.92	1.5	1.8	0.1	0.8	1.7	46.1	4.9	4.4	0	0.3	0.9	91.5	99.4	99.4	100	100	100
M14	R01	2	2	1	7	4	21.41	1.5	1.1	0.3	3	5.4	41.1	8.1	8.1	1.1	9.9	20.6	30.7	58	69.2	91.3	97.9	100
M14	R02	2	4	1	12	1	21.16	0.6	0.4	0.1	1.5	2.6	49	1.8	1.6	0.7	5.2	10	95.6	96.3	97.8	99.3	100	100
M14	R03	2	2	1	7	4	20.14	0.4	0.4	0.4	1.2	1.9	47.7	10.1	13.3	1.3	8.7	20.3	25	54.1	53.4	87.8	99.7	100
M14	R04	2	2	1	7	1	21.07	1.7	2.1	0.1	1.7	2.7	43.8	7	7.2	0.3	3.4	9.4	41.6	82.6	87	99.9	100	100
M14	R05	2	2	1	7	1	21.89	1.9	2.4	0.3	3.2	5	42.4	5.1	5.5	0.5	5.6	11.9	51.8	75.2	85.2	99.3	100	100
M14	R06	2	2	1	7	4	21.73	0.6	1.2	0.1	1.3	2.2	41.8	9	10.4	0.7	8.2	19.7	27.9	56.1	59.6	89.6	97.7	100
M14	R07	2	2	1	7	1	20.42	0.6	0.3	0.1	1.4	2.2	51.2	1.9	2.4	0.8	4.8	9.2	94.9	97.4	99.2	99.5	100	100
M14	R08	2	2	1	7	2	22.46	1.4	0.9	0.1	0.6	1.2	44.9	3.9	5.1	0.4	3.1	6	77.7	97.7	99.3	99.6	100	100

Table B1 (continuation)

Position		Types					Statistical parameters												General risk assessment					
Museum	Room	QoE	LoC	Building Type	System Type	Position Type	T annual mean	T winter drop	T summer rise	dT hour	dT day	dT week	RH annual mean	R winter drop	R summer rise	dRH hour	dRH day	dRH week	Class AA	Class As	Class A	Class B	Class C	Class D
M14	R09	2	2	1	7	1	20.6	0.1	0.2	0.2	1.5	2.1	49.4	2.5	3.2	0.8	4.7	8.8	89.7	97.2	99.4	99.6	100	100
M14	R10	2	2	1	7	1	21.02	0.5	0.3	0.1	1.6	2.2	47.9	2.8	4.3	0.6	4	7.9	85.5	96.9	99.3	99.7	100	100
M14	R11	2	2	1	7	4	22.32	1	1.4	0	0.3	1	41.4	7.7	9.3	0.4	4.7	12.7	34.5	72.1	75.2	98	99.8	100
M14	R12	2	2	1	7	4	21.38	1.4	1.7	0	0.3	1	43	7.7	9	0.3	4.1	11.7	34.2	73.7	77.1	99.1	100	100
M14	R13	2	2	1	7	4	20.22	2.5	2.6	0.1	1.2	2.9	46.2	7.1	7.2	0.4	5.3	13.8	40.5	69.6	80.1	97.9	100	100
M14	R14	2	2	1	7	1	22.76	1.3	1.3	0.2	2.4	3.4	41.6	7.6	7	0.5	5	11	43.5	77.4	81.3	99.8	100	100
M14	R15	2	2	1	7	1	22.01	1	1.5	0.1	0.8	1.7	41.4	7.8	9.3	0.7	8.7	20.5	31.7	53.9	63.6	87.4	98	100
M14	R16	2	4	1	12	1	18.81	0.3	0.3	0.1	1	1.5	57.9	1.1	1.5	0.8	4.3	8.2	97.9	98.2	99.3	99.5	100	100
M14	R17	2	4	1	12	1	19.82	0.2	0.2	0.1	1	1.6	53.4	1.7	2.5	0.5	3.4	6.8	97.5	98.3	99.4	99.5	100	100
M14	R18	2	4	1	12	1	19.03	0.4	0.4	0.1	1.2	1.8	57.6	1.2	1.6	0.8	4.8	9	97.4	97.8	99.3	99.5	100	100
M14	R19	2	4	1	12	4	21.28	0.9	1.1	0.1	0.6	1.6	44.4	8.2	9.8	0.6	6.8	17.3	32.2	64.5	68.8	94.9	99.9	100
M14	R20	2	2	1	7	4	21.24	0.6	0.9	0.1	1.1	2	45.1	8.3	10.4	0.5	6	15.4	29.8	65.2	66.3	95.4	99.9	100
M14	R21	2	2	1	7	1	20.66	0.6	0.6	0.3	3	4.2	49.3	1.9	1.2	0.7	6.8	11.2	87.4	90.1	92.9	98.8	100	100
M15	R01	1	4	2	10	3	18.69	3.5	3.3	0	0.5	1.8	57	9.3	4.9	0.2	2.1	7.1	58.3	80	88.9	98.1	100	100
M15	R02	1	4	2	10	3	19.66	3.2	3	0.1	0.9	2.4	55.7	9.3	4.2	0.6	4.1	9.8	56.8	76.2	86.9	98	100	100
M15	R03	1	4	2	10	3	18.6	2.6	3.6	0.1	1.2	2.8	55.2	16.5	8.8	0.7	6.1	13.2	34.9	54.4	61.4	93.4	99.3	99.3
M15	R04	1	4	2	10	3	17.04	2.3	2.8	0.1	1	2.3	61.2	12.3	7.2	0.8	5.3	11.4	47.3	65.1	76	95.3	98.2	98.2
M15	R05	1	4	2	10	3	19	3.8	4.6	0.4	4.1	7.2	54.4	4.9	11.6	1.2	12.5	21.8	39.7	55.1	61.3	91.1	100	100
M15	R06	1	4	2	10	3	19.61	3.7	4.1	0.3	2.9	5.5	52.7	6.9	9.7	0.9	9.2	17.7	41.7	64.1	69.1	94	100	100
M15	R07	1	4	2	10	3	19.33	3.9	4.1	0.2	1.5	3.4	53.7	7.1	9.3	0.6	6	13	41	67.9	74	95.3	100	100
M15	R08	1	4	2	10	3	18.37	2.1	2.6	0.2	2.1	4	55.7	13.2	8.3	0.9	8.1	15.6	38.1	59.4	66.4	93.6	100	100
M15	R09	1	4	2	10	3	20.56	1.9	1.7	0.1	0.8	2	46.4	5.2	4.9	1.2	7.8	17.2	54	62	80.2	87.6	99.9	100
M15	R10	1	4	2	10	3	18.86	4.9	4.6	0.1	0.7	2.3	56	2.1	2.6	0.6	4.6	11.6	72.8	75.3	82.5	94.7	99.1	99.1
M15	R11	1	4	2	10	3	19.14	4.8	4.7	0.1	0.8	2.5	53.4	2.1	2.6	0.6	4.8	12.3	71.2	73.1	80.4	93.5	98.9	98.9
M15	R12	1	4	2	10	3	19.15	3.2	4.3	0.3	1.3	3.4	54.3	7.1	4.3	1	5.7	13.5	69.7	73.7	81.3	93.7	100	100
M15	R13	1	4	2	10	3	19.67	1.5	1.9	0	0.4	1.1	48	12.5	10.8	0.3	3.5	9.9	55.5	73.5	80.1	92.3	99.5	99.5
M15	R14	1	4	2	10	3	19.25	2.1	2.7	0.1	0.8	2	52.1	11.8	9.8	0.9	7.8	16.6	52.5	61.2	79.1	88.8	96.9	96.9
M16	R01	1	2	2	2	1	23.9	1.6	1.9	0.1	1.1	2.4	41.5	14.5	17.8	0.5	4.9	13.1	18.8	51.5	40.3	83.3	93.6	100
M16	R02	1	2	2	2	1	21.68	2.4	2.9	0.6	3.6	5.9	42.9	7.6	9.7	1.1	6.2	13.3	29.6	53.9	54.1	95	99.5	100
M16	R03	1	2	2	2	1	23.34	0.9	1.1	0.1	1.1	2.1	41.3	12.9	15.5	0.5	4.9	12.1	22.9	58.4	50	91.6	94.6	100
M16	R04	1	2	2	2	4	22.03	1.9	1.2	0.3	1.8	3.6	45.6	15.3	13.9	0.7	6.2	15.2	8.9	51.5	34.1	92.4	96.8	100
M16	R05	1	2	2	2	1	22.84	2.3	2.1	0.2	1.9	3.7	43.5	15.9	15.4	0.7	6.4	14.3	15.9	43.1	34.2	84.7	92.8	100
M16	R06	1	2	2	2	3	21.31	0.4	0.3	0.1	0.5	1.2	47.2	17.4	19	0.3	3.7	10	19.3	46.4	33.8	80.1	96	100
M16	R07	1	2	2	2	3	20.46	1.1	1.1	0.1	0.5	1.3	50.7	16.2	17.3	0.5	4.5	11.4	19.8	53.6	37.5	85.8	98.4	99.3
M16	R08	1	2	2	2	1	21.8	1	1.7	0.2	1.4	2.6	44.1	12.2	13.4	0.6	5.3	13.8	20.8	54.6	48.2	92.3	97.6	100
M16	R09	1	2	2	2	1	20.77	1.2	2	0.4	3.6	6.8	47.5	12.4	13.3	1	10	22.2	21.2	50.5	48.1	88	98.7	100
M16	R10	1	2	2	2	1	20.88	1.4	2.3	0.2	1.4	2.8	45.6	11.5	12.5	0.5	5.3	13.9	24	54.7	52.5	92.6	98.7	100
M16	R11	1	2	2	2	3	18.32	4.9	4.7	0.1	1	3	50.5	7.5	6.4	0.4	3.5	9.6	46.5	71.8	76.6	98.6	100	100
M16	R12	1	2	2	2	4	23.56	1.6	2	0.9	9.3	15.6	39.3	10.4	11.2	1.7	16.8	29.1	19.1	45.3	44.5	83.9	91	100
M16	R13	1	2	2	2	2	21.23	2.8	1.2	0.1	1	2.3	50.3	2.6	2.2	0.1	1.6	2.3	89.6	89.6	89.6	100	100	100
M16	R14	1	2	2	2	2	21.98	2.8	1.6	0.1	1.6	2.8	42.6	11	12	0.1	1.7	4.8	21.2	73.7	57.6	100	98.8	100
M16	R15	1	2	2	2	1	21.23	1.8	2.4	0.2	1.9	3.5	46	9.8	10.8	0.4	4.7	11.8	21.7	64.2	56.9	97.9	99.9	100
M16	R16	1	2	2	2	1	20.66	1.6	2.5	0.1	1.1	2.6	48.2	9.6	10.8	0.4	3.8	10.7	22.8	67.1	59.1	98	100	100
M16	R17	1	2	2	2	1	23.39	1.2	0.7	0.2	1.6	2.8	40.4	13.8	15.2	0.5	5.4	14	18.2	52.6	41.4	89.2	90.8	100
M16	R18	1	2	2	2	1	22.34	1	1	0.1	1.5	2.7	42.6	13	14.1	0.5	5.6	14.4	17.5	54.1	43.6	91.3	95	100
M16	R19	1	2	2	2	1	23.36	1.4	0.7	0.2	1.7	3	40.5	14	15.2	0.6	5.8	14.3	16.4	52.2	39.2	89	90.9	100
M17	R01	4	2	4	6	1	21.56	0.9	1.2	0.3	3.8	6.3	42.5	14.2	15	0.9	10.3	22.8	15.3	32.5	30.3	77.4	90.5	100

Table B1 (continuation)

Position		Types					Statistical parameters												General risk assessment					
Museum	Room	QoE	LoC	Building Type	System Type	Position Type	T annual mean	T winter drop	T summer rise	dT hour	dT day	dT week	RH annual mean	R winter drop	R summer rise	dRH hour	dRH day	dRH week	Class AA	Class As	Class A	Class B	Class C	Class D
M17	R02	4	2	4	6	1	21.96	1	1.3	0.4	5.2	8.7	41.9	14.1	14.6	1	11.9	24.8	11.8	26.8	23.6	74.1	88.7	100
M17	R03	4	2	4	6	4	22.58	1.8	2.5	0.3	3.2	6.2	40.6	9	11.5	0.5	6.2	15.3	22.6	54.2	50.8	94.9	98.2	100
M17	R04	4	2	4	6	1	20.83	1.7	2.3	0.3	3	5.2	46	10	11.4	1	10.1	22.4	24.1	43.9	47.2	86.5	98.9	100
M17	R05	4	2	4	6	1	20.23	2.1	2.4	0.3	2.8	4.8	45.9	10.2	13.1	0.7	8.1	19.8	23.4	42.4	45.8	85.2	98.2	99.9
M17	R06	4	2	4	6	1	19.61	2.3	2.9	0.2	2.9	5.2	49.1	9.2	11.4	0.4	5.8	15.1	26.7	57.6	55.4	91.9	99.8	100
M17	R07	4	2	4	6	2	19.3	2.3	2.6	0.1	1.4	2.9	47.4	10.2	12.2	0.3	4.6	14.1	28.3	55.6	56.2	91.9	99	100
M17	R08	4	2	4	6	2	21.26	1.3	1.5	0.3	3.4	6	43.1	13	14.2	0.6	6.9	17.2	17.2	38.6	33.6	86.6	95.6	100
M18	R01	4	4	4	12	3	19.58	0.3	0.3	0	0.1	0.3	51.4	0.9	0.7	0.3	1.3	2.5	100	100	100	100	100	100
M18	R02	4	4	4	12	3	19.11	0.2	0.2	0	0.1	0.3	52.7	0.7	1.3	0.4	1.7	3.1	100	100	100	100	100	100
M18	R03	4	4	4	12	3	19.9	0.1	0.2	0	0.1	0.4	50.5	0.3	0.4	0.3	1.2	2.3	100	100	100	100	100	100
M18	R04	4	4	4	12	3	19.85	0.1	0.1	0	0.2	0.4	50.4	0.8	0.6	0.3	1.3	2.5	100	100	100	100	100	100
M18	R05	4	4	4	12	1	19.7	0.4	0.5	0	0.3	0.7	48.2	4.9	5.7	0.7	4.8	10.7	67.3	90	96.9	99.8	100	100
M18	R06	4	4	4	12	4	8.79	0.3	0.2	0.1	0.3	0.7	43.2	2.1	4.2	0.3	1.4	3.2	98.8	99.9	100	100	100	100
M18	R07	4	4	4	12	1	21.48	0.1	0.2	0.2	1.1	1.5	46.7	2.8	2.3	1	4.5	8.3	91.9	93.6	97.5	98.6	100	100
M18	R08	4	4	4	12	1	21.23	0.5	0.4	0.1	1.2	2.1	50.3	1.5	1.8	0.9	4.6	9.4	93.5	93.5	97.4	98.1	100	100
M18	R09	4	4	4	12	4	20.2	0.4	0.6	0.1	1.2	2.1	54.9	3.9	4.2	1.4	6.9	13	72.6	90.4	96.5	97.4	100	100
M19	R01	2	4	1	10	1	19.74	0.8	0.7	0.2	2.4	2.9	56.6	4.3	4.8	0.6	5.8	10.5	71.5	84.3	92.9	98	100	100
M19	R02	2	4	1	10	1	20.17	0.8	0.7	0.2	1.8	2.2	55.5	6.2	6.9	0.5	5.1	10.8	56.2	84.3	89.4	97.7	100	100
M19	R03	2	4	1	10	1	20.42	0.9	0.9	0.2	2.5	3.3	53.8	4.6	4.8	0.6	5.6	10.5	70.3	85.4	93.3	99.2	100	100
M19	R04	2	4	1	10	1	23.23	1.4	1.3	0.2	2.6	3.3	45	3.2	3.1	0.4	4.6	8.7	72.9	78.2	86.4	98.7	100	100
M19	R05	2	4	1	10	4	20.11	0.6	0.7	0.2	2.2	3	55.4	4.7	5.1	0.7	6.4	11.7	63.2	81.4	89.4	97.5	100	100
M19	R06	2	4	1	10	1	20.12	1.7	1	0.1	1.5	2.1	54.5	4.4	4.2	0.5	5	10.6	72.5	86.1	94.9	98.3	100	100
M19	R07	2	4	1	10	1	20.19	1.6	1	0.1	1.5	2.1	54.2	4.4	4.3	0.5	5.2	10.7	73.2	86.1	94.9	98.1	100	100
M19	R08	2	4	1	10	1	19.31	0.5	0.5	0.1	1.4	1.8	58.1	5.3	5.8	0.5	3.9	8.8	69.9	84.7	91.2	98	100	100
M19	R09	2	4	1	10	1	19.22	0.8	0.7	0.2	1.8	2.2	58.5	4.5	5.1	0.5	5	10.2	69.9	84.3	91.9	97.6	100	100
M19	R10	2	4	1	10	1	21.21	0.6	0.5	0.2	2.6	3.2	51.9	7	6.6	0.6	6.3	12	54.5	78.8	87.5	96.6	100	100
M20	R01	1	2	1	2	4	20.1	0.5	0.4	0	0.2	0.5	58.3	18.8	21.9	0.3	3.9	11.3	14.1	37.6	27.9	67	74.6	74.6
M20	R02	1	2	1	2	1	20.57	0.9	0.9	0.3	3	4.4	49.1	14.2	17.7	0.9	7.8	15.8	18.7	44.5	34	82.2	97.2	97.3
M20	R03	1	2	1	2	1	21.36	1.5	1.9	0.1	1.1	2.6	45.9	10.6	11.2	0.5	5.7	14.9	27.3	61.3	57.7	96.1	99.5	100
M20	R04	1	2	1	2	4	16.17	4.5	5.1	0.4	4.8	7.8	52.5	8.9	9.1	1.4	15	27.7	23.9	28.6	43	73.3	99.9	100
M20	R05	1	2	1	2	1	20.75	1.4	1.9	0.2	1.6	2.7	46.9	11.4	12	0.6	6.1	15.3	25.7	58.2	55.3	94.1	99.4	100
M20	R06	1	2	1	2	2	20.43	1.4	1.7	0.1	1.2	2.2	45.7	11.2	11.8	0.1	1.2	3.1	19.8	95.2	62.2	100	100	100
M20	R07	1	2	1	2	1	20.45	2.7	3.6	0.1	1.6	3.3	45	7.8	8.7	0.4	4.6	11.6	34.3	66.1	69.8	99.1	100	100
M20	R08	1	2	1	2	1	20.82	2.1	3.1	0.1	1.6	2.8	44.3	7.7	8.2	0.4	3.5	9.5	36.4	76	77.4	99.5	100	100
M20	R09	1	2	1	2	1	19.27	3.1	3.5	0.1	1.3	2.8	48.4	8.1	8.3	0.3	3.4	10.2	37.7	71.3	73.6	99.4	100	100
M20	R10	1	2	1	2	1	20.01	3.2	3.5	0.3	3.1	4.9	46	7	7.2	0.6	6.1	12.7	38.7	65.5	70.1	98.4	100	100
M20	R11	1	2	1	2	1	21.81	3	1.6	0.2	1.7	4.1	43.1	13.8	13.9	0.5	4.5	12	10.5	47.8	24.6	93.7	98.1	100
M21	R01	4	4	3	12	6	20.77	0.6	0.4	0.1	0.8	1.3	54.1	2.4	1.4	1.1	6	10.3	95.5	96.9	99.4	99.6	100	100
M21	R02	4	4	3	12	4	20.97	0.6	1.2	0.3	1.7	2.4	51	6.1	5.9	1.4	7.8	15.3	67	82.1	88.3	96.3	99.6	99.6
M21	R03	4	4	3	12	6	21.24	0.6	0.6	1.5	2.6	3.6	50.3	10.1	9.2	4.5	11.5	19.9	50.7	67.1	76.5	95.2	99.3	99.3
M21	R04	4	4	3	12	1	20.55	0.7	1.8	0.2	1	1.8	53.3	14.3	7	1.1	6.8	14.6	57.9	75.1	79.8	94.9	99.5	99.5
M21	R05	4	4	3	12	1	20.87	0.7	1.7	0.2	1.1	2	52.3	14.8	7.5	1.2	7	15.1	53.7	74.2	78.3	94	99.5	99.5
M21	R06	4	4	3	12	1	20.17	0.3	0.3	0.1	0.9	1.6	55	4.7	4.5	1.2	6.6	14	76.1	85.4	93.1	97	99.6	99.6
M21	R07	4	4	3	12	1	20.4	1.9	0.8	0.3	2	3.1	54.9	6.4	5.5	1.6	8.6	16.2	67.7	82.5	90.3	95.4	99.7	99.7
M21	R08	4	4	3	12	1	20.15	1	0.5	0.2	1.3	2.3	55.5	5	3.1	1.5	7.8	15.3	75.7	81.9	91.8	95.1	99.7	99.7
M21	R09	4	4	3	12	1	20.47	0.7	0.6	0.4	1.5	2.3	53.4	6	6.9	1.6	8.2	16.3	64.6	80.9	86.5	95.9	99.5	99.5
M21	R10	4	4	3	12	1	20.15	0.6	0.6	0.3	1.6	2.5	54.3	6	6.4	1.7	8.7	16.8	64.4	79.4	87.2	95.5	99.5	99.5

Table B1 (continuation)

Position		Types					Statistical parameters												General risk assessment					
Museum	Room	QoE	LoC	Building Type	System Type	Position Type	T annual mean	T winter drop	T summer rise	dT hour	dT day	dT week	RH annual mean	R winter drop	R summer rise	dRH hour	dRH day	dRH week	Class AA	Class As	Class A	Class B	Class C	Class D
M21	R11	4	4	3	12	1	20.49	0.4	0.3	0.3	1.3	2	54.2	5.7	5.9	1.5	7.7	15.7	69.7	82	89.4	96.4	99.5	99.5
M21	R12	4	4	3	12	2	21.03	0.8	0.5	0.1	0.9	1.7	54.9	3.5	2.4	0.1	0.8	1.4	97.9	99.3	99.3	100	100	100
M21	R13	4	4	3	12	1	20.16	0.5	0.6	0.1	1.3	2.1	62.7	3	3.5	1.2	6.8	13.5	79.4	85.3	96.3	98.4	99.1	99.1
M21	R14	4	4	3	12	1	19.8	0.5	0.5	0.2	1.3	2.2	63.8	6.5	6.1	1.8	8.6	16	65.8	80	90.2	97.3	96.1	96.1
M21	R15	4	4	3	12	4	21.78	0.7	0.8	0.3	2.4	3.3	50.1	3.7	4.1	1.8	10.9	18.9	70.7	71.7	89.5	94.9	99.8	99.8
M21	R16	4	4	3	12	4	21.72	0.6	0.8	0.3	2.5	3.4	51.3	3.5	3.8	1.8	11.1	18.9	71.2	70.9	89.7	94.9	99.7	99.7
M21	R17	4	4	3	12	6	18.35	0.8	0.7	1.2	4.7	6.9	62.5	4.6	6.2	6.5	23	34.7	40.8	45.9	64.6	78.3	89.6	89.6
M21	R18	4	4	3	12	6	20.84	0.4	0.4	0.4	2	3	52.6	4.6	5.1	2.3	11.1	19.5	68.7	73.6	88.8	94.7	99.6	99.6
M21	R19	4	4	3	12	1	20.27	0.6	0.7	0.1	1.2	1.9	53.7	3.4	3.7	1.3	7.6	15.3	77.6	81.6	94.4	96.8	99.8	99.8
M21	R20	4	4	3	12	1	20.46	0.7	0.8	0.2	1.7	2.5	53.5	3.6	3.5	1.3	8.3	15.6	77.2	80	93	96.5	99.7	99.7
M21	R21	4	4	4	12	4	22.39	1.9	2.3	0.3	3.2	4.1	47.9	5.2	3.9	1.8	12.6	20	39.2	45.6	62.6	78.5	100	100
M21	R22	4	4	4	12	4	22.1	0.7	0.6	0.1	0.8	1.5	48.9	6.9	7	1.6	8	15.7	58.1	72.2	83.7	96.4	100	100
M21	R23	4	4	4	12	3	19.12	0.5	0.5	0.1	0.6	1	53.8	3.8	6.5	1.3	6.8	12.9	82.9	91.1	94.2	97.9	99.9	99.9
M21	R24	4	4	4	12	6	20.17	1.2	2.1	1.2	2.9	4.3	49.3	8.6	8.6	5	15.6	24.6	42.3	69.1	72.2	93.8	99.8	99.8
M21	R25	4	4	4	12	3	19.01	0.3	0.3	0.1	0.5	1	54.8	3	4.8	1	4.8	9.1	91.1	95.1	97.4	98.8	100	100
M21	R26	4	4	4	12	6	18.93	0.7	0.9	0.8	2.4	3.6	55	4.5	5.8	3.4	11.6	18.3	74.9	80.9	88.1	97.3	99.6	99.6
M21	R27	4	4	4	12	3	19.95	0.5	1	0	0.3	0.8	53.3	3.2	4.4	0.5	3.6	7.7	89.4	95.5	97.5	99.3	100	100
M21	R28	4	4	4	12	6	18.94	0.5	1	0.2	1.1	2.4	54.5	3.6	3.8	1.9	8.5	15	81.8	86.8	93.6	98.6	100	100
M21	R29	4	4	4	12	3	19.55	0.5	0.6	0.1	0.4	0.9	52.5	7.7	7.2	0.7	4.9	11.3	61	85.7	89.1	99	100	100
M21	R30	4	4	4	12	6	19.36	1.6	2.3	1.1	4.2	6.5	49.4	9.4	11.5	4.1	17.2	28.8	21.1	36.9	39.2	80.1	99.3	99.4
M21	R31	4	4	4	12	1	21.62	0.6	0.5	0.2	0.8	1.4	51.1	3.6	4.2	1.2	5.5	11.1	85.9	90.5	97.5	99.1	100	100
M21	R32	4	4	4	12	1	21.16	0.4	0.2	0.1	0.6	1.2	54.7	5	5	1.2	5.4	11.3	75.8	87.8	95.7	98.6	99.7	99.7
M21	R33	4	4	4	12	4	18.32	2.6	2.6	0.2	1.8	3.3	52.8	8.9	6.1	1.4	11.1	22.4	47.6	52.1	74.7	88.5	99.8	99.8
M21	R34	4	4	4	12	6	21.72	1.1	1.2	1.3	3.5	5.1	52.4	7.4	3	4.5	13.8	21	56.2	64.8	83	96.4	99.9	99.9
M21	R35	4	4	4	12	1	21.89	1.4	0.9	0.7	2.4	3.9	50.6	7	4.2	2.4	8.9	16.3	68.2	75.8	87.6	96.4	99.9	99.9
M21	R36	4	4	4	12	1	20.11	2.5	2	0.5	2.3	3.4	57.9	3.5	2.1	1.9	8.2	14.5	78.4	78.5	89.9	98.3	99.8	99.8
M21	R37	4	4	4	12	6	21.24	0.6	0.6	1.5	2.6	3.6	50.3	10.1	9.2	4.5	11.5	19.9	50.7	67.1	76.5	95.2	99.3	99.3
M21	R38	4	4	4	12	1	20.64	0.4	0.2	0.3	0.7	1.3	50.9	5.6	7.2	1.2	6.6	14.1	65	81.8	88.1	97.8	99.7	99.7
M21	R39	4	4	4	12	4	20.28	0.8	1	0.3	1	1.8	51.5	6.6	5.4	1.2	7.3	14.9	71.2	79.6	90.3	97.8	99.9	99.9

Table B2: Results for average room conditions: Position, climate class propertie and object risk assessment.s

Position		General risk assessment						Specific risk assessment											
Museum	Room	Class AA	Class As	Class A	Class B	Class C	Class D	Paper Mould	Paper LM	Painting Mould	Painting LM	Painting Base	Painting Pict	Furniture Mould	Furniture LM	Furniture Base	Sculpture Mould	Sculpture LM	Sculpture Base
M01	R01	56	72.9	78.6	98.4	100	100	0	0.86	0	0.88	0	0	0	0.88	0	0	0.87	0
M01	R02	50.2	74.4	80.4	98.4	100	100	0	0.84	0	0.87	0	0	0	0.88	0	0	0.87	0
M01	R03	58.8	74.9	81.1	98.7	100	100	0	0.84	0	0.88	0	0	0	0.88	0	0	0.87	0
M01	R04	57.3	74	79.9	97.9	100	100	G?	0.84	G?	0.87	0	0	G?	0.88	0	G?	0.87	0
M01	R05	44.2	60.7	71	96.9	100	100	0	0.82	0	0.88	0	0	0	0.89	0	0	0.88	0
M01	R06	32.3	50.8	60.7	94.7	100	100	0	0.82	0	0.9	0	0	0	0.91	0	0	0.9	0
M01	R07	53.8	73	82.2	98.7	100	100	0	0.81	0	0.86	0	0	0	0.86	0	0	0.86	0
M01	R08	35.3	55.5	65.3	94.2	100	100	0	0.87	0	0.92	0	0	0	0.92	0	0	0.92	0
M02	R01	47.2	58.8	72.5	97.9	100	100	0	1.48	0	1.35	0	0	0	1.35	0	0	1.35	0
M02	R02	59.2	70.1	78.4	99.7	100	100	0	1.41	0	1.32	0	0	0	1.32	0	0	1.32	0
M02	R03	60	65.6	80.2	96.1	100	100	0	1.48	0	1.28	1	0	0	1.29	0	0	1.28	0
M02	R04	18.6	41.1	43.1	79.3	99.6	100	0	1.17	0	1.14	0	1	0	1.14	0	0	1.15	1
M02	R05	53.1	55.4	80.8	92.3	96.4	96.4	0	1.39	0	1.2	1	0	0	1.2	0	0	1.19	1
M02	R06	49.7	53.3	75.1	87.6	88.1	88.1	G?	1.41	G?	1.19	1	0	G?	1.19	0	G?	1.19	1
M02	R07	51.2	61.5	75.6	97.5	98.9	98.9	0	1.31	0	1.18	1	0	0	1.18	0	0	1.18	0
M02	R08	39.7	53.5	68.2	93.8	94.4	94.4	0	1.27	0	1.13	1	0	0	1.13	0	0	1.13	1
M02	R09	50.1	57.3	74.5	92.9	97.2	97.2	0	1.28	0	1.15	1	0	0	1.16	0	0	1.14	1
M02	R10	48.9	58.2	71.7	95.9	96.4	96.4	0	1.36	0	1.2	1	0	0	1.2	0	0	1.2	0
M02	R11	61	72.2	78.5	99.8	100	100	0	1.43	0	1.32	0	0	0	1.32	0	0	1.32	0
M02	R12	45.3	54.8	79.7	89	63.5	63.5	G?	1.48	G?	1.18	1	0	G?	1.18	0	G?	1.18	1
M02	R13	53.2	57.7	82.6	93.8	62	62	G?	1.62	G?	1.26	1	0	G?	1.26	0	G?	1.26	1
M02	R14	47.1	56.6	79.6	89.2	59.5	59.5	19	1.4	19	1.13	1	0	19	1.13	0	19	1.13	1
M02	R15	42.6	53.9	76.7	89.5	77.5	77.5	G?	1.38	G?	1.14	1	0	G?	1.14	0	G?	1.14	1
M02	R16	42.7	48.4	71.1	90.3	100	100	0	1.31	0	1.27	0	0	0	1.27	0	0	1.27	1
M02	R17	16.7	34.7	33.5	73.9	97.4	98	0	1.29	0	1.18	1	1	0	1.18	0	0	1.18	1
M02	R18	41.3	50	63.7	84.8	99.8	99.8	0	1.28	0	1.18	1	1	0	1.18	0	0	1.18	1
M02	R19	48	55.1	81.1	90	57.1	57.1	G?	1.47	G?	1.17	1	0	G?	1.17	0	G?	1.17	1
M02	R20	46.2	50.9	74.2	89.6	58.8	58.8	G?	1.47	G?	1.19	1	0	G?	1.19	0	G?	1.18	1
M02	R21	12.5	26.9	29.4	75	77.1	77.1	G?	1.31	G?	1.18	1	1	G?	1.18	0	G?	1.18	1
M02	R22	46.5	57.3	71.5	92.9	98.1	98.1	0	1.3	0	1.17	1	0	0	1.18	0	0	1.17	1
M04	R01	79	88.6	95.2	95.3	100	100	0	1.46	0	1.51	0	0	0	1.52	0	0	1.51	0
M04	R02	25.6	39.2	47	85.2	99.9	100	0	1.05	0	1.05	0	0	0	1.05	0	0	1.05	1
M04	R03	27.1	55.3	54.1	92.5	99.3	100	0	0.94	0	0.98	0	1	0	0.99	0	0	0.98	0
M04	R04	47.7	59.3	72.6	97.6	100	100	0	0.97	0	0.94	0	0	0	0.95	0	0	0.94	0
M04	R05	40.6	55.3	66	96.5	100	100	0	0.9	0	0.92	0	0	0	0.93	0	0	0.93	0
M04	R06	61.9	75.7	83.9	98.9	100	100	0	0.8	0	0.86	0	0	0	0.86	0	0	0.86	0
M04	R07	51.3	74	81	98.7	100	100	0	0.79	0	0.86	0	0	0	0.87	0	0	0.86	0
M04	R08	30.1	85.4	84.9	99.8	100	100	0	0.73	0	0.78	0	0	0	0.79	0	0	0.78	0
M04	R09	38.5	73.3	72.9	99.1	100	100	0	0.83	0	0.9	0	0	0	0.91	0	0	0.9	0
M04	R10	25.6	47.6	55.6	89.2	100	100	0	0.97	0	0.96	0	0	0	0.97	0	0	0.96	0
M05	R01	18.6	50.4	44.9	88.4	85.9	100	0	0.89	0	1.02	0	1	0	1.03	0	0	1.02	0
M05	R02	68.4	78	92.8	98.5	99.8	99.8	0	1.25	0	1.1	1	0	0	1.1	0	0	1.1	0
M05	R03	47.2	63	71.8	97.1	92.4	92.4	0	1.35	0	1.18	1	0	0	1.18	0	0	1.18	0
M05	R04	46	49.8	77.4	88.1	60	60	G?	1.35	G?	1.11	1	0	G?	1.11	0	G?	1.11	1
M05	R05	26.8	54.5	53.9	94.1	98.4	100	0	0.91	0	1.01	0	1	0	1.02	0	0	1.01	0
M05	R06	59.6	67.7	81.2	97.6	98.5	98.5	0	1.22	0	1.1	1	0	0	1.1	0	0	1.1	0
M05	R07	29.4	51.5	54.4	85.4	97.3	97.3	0	1.07	0	1.01	1	1	0	1.02	0	0	1.01	0

Table B2 (continuation)

Position		General risk assessment						Specific risk assessment											
Museum	Room	Class AA	Class As	Class A	Class B	Class C	Class D	Paper Mould	Paper LM	Painting Mould	Painting LM	Painting Base	Painting Pict	Furniture Mould	Furniture LM	Furniture Base	Sculpture Mould	Sculpture LM	Sculpture Base
M05	R08	15.7	31.5	32.1	84.2	70.6	70.6	G?	1.22	G?	1.1	1	1	G?	1.1	0	G?	1.11	1
M06	R01	15.4	34.9	35	73.9	92.3	99.7	0	1.02	0	1.05	1	1	0	1.06	0	0	1.05	1
M06	R02	20.7	33.5	37.7	82.1	96.4	100	0	1.1	0	1.12	1	1	0	1.13	0	0	1.12	0
M06	R03	16.6	34.4	35.2	75.6	92.2	100	0	1.05	0	1.08	1	1	0	1.09	0	0	1.08	1
M06	R04	10.7	25.2	24.9	65.9	86	99.9	0	1.08	0	1.11	1	1	0	1.11	0	0	1.12	1
M06	R05	15.6	30.1	32	75.3	88.3	100	0	1.03	0	1.09	1	1	0	1.1	0	0	1.09	0
M06	R06	10.9	28.2	25.5	69.8	85.4	100	0	1.11	0	1.15	1	1	0	1.15	0	0	1.16	1
M06	R07	14.7	32	32.7	71.6	91.9	100	0	1	0	1.04	1	1	0	1.04	0	0	1.04	1
M06	R08	13.3	33.4	30.3	76.2	90.7	99.8	0	1.02	0	1.05	1	1	0	1.06	0	0	1.06	1
M06	R09	9	28.8	22.6	66.5	87.7	99.9	0	0.99	0	1.03	1	2	0	1.03	0	0	1.04	1
M06	R10	21.4	25.6	33.8	67	95.7	98.6	0	1.04	0	1.05	1	1	0	1.06	0	0	1.06	1
M06	R11	13.7	36.3	32.3	76.5	88.7	100	0	1.01	0	1.06	1	1	0	1.07	0	0	1.06	0
M06	R12	10	31.2	26.9	69.9	90.4	100	0	1.04	0	1.07	1	1	0	1.07	0	0	1.07	0
M06	R13	12.5	31	29.2	72.5	84.3	100	0	1	0	1.07	1	1	0	1.07	0	0	1.08	1
M07	R01	39	49.4	68.9	86.5	100	100	0	1.11	0	1.11	0	0	0	1.11	0	0	1.12	1
M07	R02	73.9	83.7	90.9	96.2	99.9	100	0	1.24	0	1.17	0	1	0	1.18	0	0	1.17	0
M07	R03	65.9	86.6	93.5	98.3	100	100	0	1.12	0	1.13	0	0	0	1.14	0	0	1.13	0
M07	R04	88.2	98	97.9	100	100	100	0	1.14	0	1.12	0	0	0	1.12	0	0	1.12	0
M07	R05	85.7	97.7	98.6	100	100	100	0	1.1	0	1.12	0	0	0	1.11	0	0	1.12	0
M07	R06	72.4	79.8	91	95.8	100	100	0	1.16	0	1.15	0	0	0	1.15	0	0	1.15	0
M07	R07	38.3	65.4	72.7	89.8	99.9	100	0	1.35	0	1.18	0	1	0	1.19	0	0	1.18	1
M07	R08	71	82	90.4	98	99.2	100	0	1.13	0	1.15	0	0	0	1.16	0	0	1.15	0
M07	R09	75.9	86	92.4	98.2	100	100	0	1.08	0	1.1	0	0	0	1.1	0	0	1.1	0
M07	R10	71.8	81.8	89.6	97.9	99.6	100	0	1.05	0	1.09	0	0	0	1.1	0	0	1.09	0
M07	R11	73.9	79.5	90.4	95.5	99.8	100	0	1.13	0	1.11	0	0	0	1.12	0	0	1.11	0
M07	R12	34	63.8	64.7	88.4	99.8	99.9	0	1.36	0	1.18	1	1	0	1.19	0	0	1.18	1
M07	R13	75.1	82	91.9	96.1	99.8	100	0	1.14	0	1.13	0	0	0	1.13	0	0	1.12	0
M07	R14	65.9	75.9	86.6	96.2	99.6	100	0	1.11	0	1.11	0	0	0	1.12	0	0	1.12	0
M07	R15	73	82.8	88.7	97.1	99.1	100	0	1.1	0	1.11	0	0	0	1.12	0	0	1.11	0
M07	R16	83.3	87.4	92.9	98	99.9	100	0	1.1	0	1.11	0	0	0	1.12	0	0	1.11	0
M07	R17	73.2	81.4	88.5	97.7	99.7	100	0	1.11	0	1.14	0	0	0	1.15	0	0	1.14	0
M07	R18	68.1	74.4	82.9	97.4	97.6	100	0	0.98	0	1.08	0	0	0	1.09	0	0	1.08	0
M07	R19	74.6	81.3	88	98	99.3	100	0	1.07	0	1.13	0	0	0	1.14	0	0	1.13	0
M08	R01	39.7	62	74.6	96.8	100	100	0	0.9	0	0.96	0	0	0	0.98	0	0	0.96	0
M08	R02	43.3	50.6	70.5	94.9	99.2	99.2	0	1.09	0	1.04	1	0	0	1.04	0	0	1.04	0
M08	R03	27.7	38.3	52.3	88.6	91.3	91.3	G?	1.12	G?	1.05	1	0	G?	1.06	0	G?	1.06	1
M08	R04	27.8	53.3	60.5	96.3	92.2	92.2	0	1.12	0	1.06	1	0	0	1.06	0	0	1.06	1
M08	R05	23.9	40.4	43.7	91.6	85	85	G?	1.17	G?	1.09	1	1	G?	1.09	0	G?	1.09	1
M08	R06	26.8	42.7	47.5	92.8	90	90	G?	1.09	G?	1.05	1	1	G?	1.05	0	G?	1.05	1
M08	R07	17.1	39.7	39.6	93.1	86.1	86.1	G?	1.11	G?	1.06	1	1	G?	1.06	0	G?	1.07	1
M08	R08	19.6	46.9	44.5	96.8	83.9	83.9	0	1.13	0	1.07	1	1	0	1.07	0	0	1.07	0
M08	R09	25	57.1	56.4	97.9	79.9	79.9	0	1.18	0	1.07	1	0	0	1.07	0	0	1.07	0
M08	R10	35.4	54.3	61.3	95.4	82.5	82.5	G?	1.15	G?	1.04	1	1	G?	1.03	0	G?	1.04	1
M08	R11	28.1	49	53	97.3	91.5	91.5	0	1.14	0	1.07	1	1	0	1.07	0	0	1.08	0
M08	R12	35.7	57.5	63.3	96.9	39.6	39.6	10	1.37	10	1.12	1	0	10	1.12	0	10	1.12	1
M08	R13	33.6	42.1	57.7	89.5	83.6	83.6	G?	1.27	G?	1.11	1	0	G?	1.11	0	G?	1.11	1
M08	R14	37.6	47.7	64.2	93.7	87.3	87.3	G?	1.28	G?	1.12	1	0	G?	1.12	0	G?	1.12	1

Table B2 (continuation)

Position		General risk assessment						Specific risk assessment											
Museum	Room	Class AA	Class As	Class A	Class B	Class C	Class D	Paper Mould	Paper LM	Painting Mould	Painting LM	Painting Base	Painting Pict	Furniture Mould	Furniture LM	Furniture Base	Sculpture Mould	Sculpture LM	Sculpture Base
M08	R15	36.7	47.9	64	94	82.4	82.4	0	1.23	0	1.08	1	0	0	1.08	0	0	1.08	0
M08	R16	51.4	60.3	81.3	96.5	96.8	96.8	0	1.11	0	1.02	1	0	0	1.01	0	0	1.02	0
M08	R17	39.7	44.6	69.9	89	98.6	98.6	0	1.04	0	1	1	0	0	1	0	0	1	1
M09	R01	14.3	44.9	32.9	89.2	99.9	99.9	0	0.95	0	0.98	0	1	0	0.98	0	0	0.98	0
M09	R02	34.6	40.3	61.6	82.4	93.2	93.2	0	1.1	0	1.01	1	0	0	1.02	0	0	1.01	1
M09	R03	17	43.1	34	93.1	100	100	0	0.91	0	0.96	0	1	0	0.96	0	0	0.96	0
M09	R04	31.7	48.4	55.7	92.8	99.2	99.2	0	1.04	0	1.01	1	0	0	1.01	0	0	1.01	1
M09	R05	26.2	53.1	53.4	89.7	100	100	0	1	0	1	0	0	0	1.01	0	0	1	0
M09	R06	21.8	47.2	46	86	60.1	60.1	G?	1.2	G?	1.05	1	1	G?	1.04	0	G?	1.05	1
M09	R07	27.6	56.8	53.5	95.5	83.1	83.1	0	1.21	0	1.08	1	0	0	1.09	0	0	1.08	0
M09	R08	20.8	45.6	39.1	90.8	74.7	74.7	G?	1.14	G?	1.05	1	1	G?	1.05	0	G?	1.05	0
M09	R09	21.8	48.4	42.3	92	51.9	51.9	G?	1.19	G?	1.05	1	1	G?	1.04	0	G?	1.05	1
M09	R10	12.1	38.4	27.2	83.3	64.9	64.9	G?	1.07	G?	1.01	1	1	G?	1	0	G?	1.02	0
M10	R01	55.6	68.7	85.5	96.7	100	100	0	0.93	0	0.93	0	0	0	0.93	0	0	0.93	0
M10	R02	68	84.7	95.1	98.6	100	100	0	1.06	0	0.97	1	0	0	0.97	0	0	0.96	0
M10	R03	22.5	63.1	55.4	88.6	95	95.2	G?	0.97	G?	0.94	1	1	G?	0.93	0	G?	0.94	1
M10	R04	57.7	63.2	82.7	91.5	99.8	99.8	0	1.02	0	0.98	0	0	0	0.98	0	0	0.98	1
M10	R05	52.7	65.3	83	91.3	99.6	99.6	0	0.97	0	0.94	1	0	0	0.94	0	0	0.94	1
M10	R06	52.1	62.8	81.2	90.7	99	99	0	1.02	0	0.95	1	0	0	0.95	0	0	0.95	1
M10	R07	42.2	57.1	68.3	88.8	99.9	99.9	G?	0.95	G?	0.93	0	0	G?	0.92	0	G?	0.93	1
M10	R08	36.1	66.3	63.7	92.4	97.7	97.7	G?	1	G?	0.94	1	0	G?	0.94	0	G?	0.94	1
M10	R09	52.1	69.7	82	93.9	99.9	100	0	0.92	0	0.94	0	0	0	0.94	0	0	0.94	1
M10	R10	54.8	69.2	81.6	94.7	100	100	0	0.96	0	0.95	0	0	0	0.95	0	0	0.95	1
M10	R11	53.7	62.9	82.4	89.8	99	99	0	1.02	0	0.96	1	0	0	0.96	0	0	0.96	1
M10	R12	51.3	55.1	77.2	88.1	97.4	97.4	0	1.02	0	0.95	1	0	0	0.95	0	0	0.95	1
M11	R01	43.9	77.8	84.6	93	29.3	100	0	1.5	0	1.8	0	1	0	1.63	0	0	1.84	0
M11	R02	23	60.1	54.9	91.2	96.9	100	0	1	0	1.03	0	1	0	1.02	0	0	1.04	0
M11	R03	18	35.7	34.6	74.6	95	95.3	0	0.92	0	0.92	1	1	0	0.91	0	0	0.92	1
M11	R04	28.9	58.3	48.6	90.3	96.6	100	0	0.9	0	0.95	0	1	0	0.93	0	0	0.95	0
M11	R05	24.6	53.3	49.6	91.9	96.3	100	0	1.13	0	1.12	0	1	0	1.1	0	0	1.13	0
M11	R06	32.5	63.3	64.3	95	95.8	100	0	1.08	0	1.1	0	1	0	1.08	0	0	1.1	0
M11	R07	31.1	53.9	61.7	93.4	99.4	100	0	1.15	0	1.14	0	1	0	1.14	0	0	1.15	0
M11	R08	34.5	74.4	64.8	97.7	99.3	100	0	1.12	0	1.12	0	1	0	1.11	0	0	1.12	0
M11	R09	25.8	62.7	65.2	98.4	99.9	100	0	1.11	0	1.12	0	1	0	1.11	0	0	1.12	0
M11	R10	39	82.5	75	100	100	100	0	1.16	0	1.16	0	0	0	1.16	0	0	1.16	0
M11	R11	25.6	46.2	36.8	84	86.1	100	0	1.15	0	1.18	0	1	0	1.15	0	0	1.18	0
M11	R12	31.6	76.6	52.6	99.8	99	100	0	1.16	0	1.16	0	1	0	1.14	0	0	1.16	0
M11	R13	29.3	76.8	51.1	99.9	98.4	100	0	1.15	0	1.17	0	1	0	1.15	0	0	1.17	0
M11	R14	22.9	41.3	37	85.4	92.2	100	0	1.06	0	1.09	0	1	0	1.08	0	0	1.1	1
M11	R15	20.2	47.8	31.2	88.9	75.1	100	0	1.07	0	1.14	0	1	0	1.1	0	0	1.15	0
M12	R01	95.5	96.6	99.2	99.5	100	100	0	0.88	0	0.89	0	0	0	0.89	0	0	0.89	0
M12	R02	95.1	96.7	98.2	99.3	100	100	0	0.85	0	0.87	0	0	0	0.87	0	0	0.87	0
M12	R03	69	86.1	94.8	99.6	100	100	0	0.7	0	0.82	0	0	0	0.82	0	0	0.82	0
M12	R04	75.9	87.2	96.6	99.1	100	100	0	0.79	0	0.86	0	0	0	0.86	0	0	0.86	0
M12	R05	74.9	83.2	93.7	100	100	100	0	0.91	0	0.89	0	0	0	0.89	0	0	0.89	0
M12	R06	74	90.4	95.8	99.8	100	100	0	0.87	0	0.91	0	0	0	0.92	0	0	0.91	0
M12	R07	73.5	88.4	96.3	99.5	100	100	0	0.83	0	0.87	0	0	0	0.88	0	0	0.87	0

Table B2 (continuation)

Position		General risk assessment						Specific risk assessment											
Museum	Room	Class AA	Class As	Class A	Class B	Class C	Class D	Paper Mould	Paper LM	Painting Mould	Painting LM	Painting Base	Painting Pict	Furniture Mould	Furniture LM	Furniture Base	Sculpture Mould	Sculpture LM	Sculpture Base
M12	R08	69.5	95	96.4	100	100	100	0	0.88	0	0.92	0	0	0	0.92	0	0	0.92	0
M12	R09	99.6	99.6	99.6	100	100	100	0	0.8	0	0.81	0	0	0	0.81	0	0	0.81	0
M12	R10	78.3	96.2	97	100	100	100	0	0.93	0	0.92	0	0	0	0.92	0	0	0.92	0
M12	R11	64.4	92.1	90.6	99.5	100	100	0	0.87	0	0.88	0	0	0	0.88	0	0	0.89	0
M12	R12	84	95.2	96.5	99.4	100	100	0	0.86	0	0.86	0	0	0	0.86	0	0	0.86	0
M12	R13	76.9	96.7	98.4	100	100	100	0	0.93	0	0.91	0	0	0	0.91	0	0	0.91	0
M12	R14	97.7	98.6	99.9	100	100	100	0	0.86	0	0.89	0	0	0	0.89	0	0	0.89	0
M12	R15	99	99.2	100	100	100	100	0	0.95	0	0.93	0	0	0	0.92	0	0	0.93	0
M12	R16	97.9	98.6	99.9	100	100	100	0	0.9	0	0.91	0	0	0	0.91	0	0	0.91	0
M12	R17	98.4	99.3	100	100	100	100	0	0.9	0	0.9	0	0	0	0.9	0	0	0.9	0
M12	R18	99.1	99	100	100	100	100	0	0.9	0	0.89	0	0	0	0.89	0	0	0.89	0
M12	R19	98.8	99.1	99.9	100	100	100	0	0.88	0	0.88	0	0	0	0.88	0	0	0.88	0
M12	R20	98	98.6	99.9	100	100	100	0	0.86	0	0.88	0	0	0	0.88	0	0	0.88	0
M12	R21	98	98.9	100	100	100	100	0	0.89	0	0.89	0	0	0	0.89	0	0	0.89	0
M12	R22	98.7	98.8	100	100	100	100	0	0.88	0	0.88	0	0	0	0.88	0	0	0.88	0
M12	R23	97.6	98.9	100	100	100	100	0	0.85	0	0.87	0	0	0	0.87	0	0	0.87	0
M12	R24	98.4	98.5	100	100	100	100	0	0.89	0	0.89	0	0	0	0.89	0	0	0.89	0
M12	R25	98.5	98.8	100	100	100	100	0	0.88	0	0.88	0	0	0	0.88	0	0	0.88	0
M12	R26	97.2	97.6	99.9	100	100	100	0	0.9	0	0.89	0	0	0	0.89	0	0	0.89	0
M12	R27	97.3	98.6	99.8	100	100	100	0	0.89	0	0.9	0	0	0	0.91	0	0	0.9	0
M12	R28	98.8	99	99.9	100	100	100	0	0.89	0	0.9	0	0	0	0.9	0	0	0.9	0
M12	R29	86	92.4	96	98.9	100	100	0	0.85	0	0.86	0	0	0	0.86	0	0	0.87	0
M13	R01	35	88.4	90.3	99.8	100	100	0	0.87	0	0.94	0	0	0	0.95	0	0	0.94	0
M13	R02	26.4	98.4	87.7	99.8	100	100	0	0.91	0	0.97	0	0	0	0.97	0	0	0.97	0
M13	R03	31	76.2	75.9	95.6	100	100	0	0.91	0	0.94	0	0	0	0.94	0	0	0.94	0
M13	R04	39.7	96.7	90.9	100	100	100	0	0.93	0	1	0	0	0	1	0	0	1	0
M13	R05	91.5	99.4	99.4	100	100	100	0	0.95	0	1	0	0	0	1	0	0	1	0
M14	R01	30.7	58	69.2	91.3	97.9	100	0	1.04	0	1.1	0	0	0	1.11	0	0	1.11	0
M14	R02	95.6	96.3	97.8	99.3	100	100	0	0.87	0	0.92	0	0	0	0.92	0	0	0.92	0
M14	R03	25	54.1	53.4	87.8	99.7	100	0	1.02	0	1.03	0	1	0	1.04	0	0	1.03	0
M14	R04	41.6	82.6	87	99.9	100	100	0	0.97	0	1.03	0	0	0	1.04	0	0	1.03	0
M14	R05	51.8	75.2	85.2	99.3	100	100	0	0.9	0	1	0	0	0	1	0	0	1	0
M14	R06	27.9	56.1	59.6	89.6	97.7	100	0	0.96	0	1.04	1	0	0	1.05	0	0	1.04	0
M14	R07	94.9	97.4	99.2	99.5	100	100	0	0.91	0	0.93	0	0	0	0.93	0	0	0.93	0
M14	R08	77.7	97.7	99.3	99.6	100	100	0	0.81	0	0.91	0	0	0	0.91	0	0	0.91	0
M14	R09	89.7	97.2	99.4	99.6	100	100	0	0.93	0	0.96	0	0	0	0.96	0	0	0.96	0
M14	R10	85.5	96.9	99.3	99.7	100	100	0	0.92	0	0.96	0	0	0	0.96	0	0	0.96	0
M14	R11	34.5	72.1	75.2	98	99.8	100	0	0.88	0	0.99	0	0	0	0.99	0	0	0.99	0
M14	R12	34.2	73.7	77.1	99.1	100	100	0	0.95	0	1.03	0	0	0	1.03	0	0	1.02	0
M14	R13	40.5	69.6	80.1	97.9	100	100	0	1	0	1.04	0	0	0	1.05	0	0	1.04	0
M14	R14	43.5	77.4	81.3	99.8	100	100	0	0.84	0	0.95	0	0	0	0.95	0	0	0.95	0
M14	R15	31.7	53.9	63.6	87.4	98	100	0	0.92	0	1.02	0	0	0	1.03	0	0	1.02	0
M14	R16	97.9	98.2	99.3	99.5	100	100	0	0.97	0	0.93	0	0	0	0.93	0	0	0.93	0
M14	R17	97.5	98.3	99.4	99.5	100	100	0	0.94	0	0.93	0	0	0	0.93	0	0	0.93	0
M14	R18	97.4	97.8	99.3	99.5	100	100	0	0.95	0	0.91	0	0	0	0.91	0	0	0.91	0
M14	R19	32.2	64.5	68.8	94.9	99.9	100	0	0.94	0	1.01	0	0	0	1.01	0	0	1	0
M14	R20	29.8	65.2	66.3	95.4	99.9	100	0	0.93	0	0.99	0	0	0	1	0	0	0.99	0

Table B2 (continuation)

Position		General risk assessment						Specific risk assessment											
Museum	Room	Class AA	Class As	Class A	Class B	Class C	Class D	Paper Mould	Paper LM	Painting Mould	Painting LM	Painting Base	Painting Pict	Furniture Mould	Furniture LM	Furniture Base	Sculpture Mould	Sculpture LM	Sculpture Base
M14	R21	87.4	90.1	92.9	98.8	100	100	0	0.92	0	0.95	0	0	0	0.95	0	0	0.95	0
M15	R01	58.3	80	88.9	98.1	100	100	0	0.93	0	0.92	0	0	0	0.92	0	0	0.92	0
M15	R02	56.8	76.2	86.9	98	100	100	0	0.84	0	0.86	0	0	0	0.86	0	0	0.86	0
M15	R03	34.9	54.4	61.4	93.4	99.3	99.3	0	1.03	0	0.99	1	1	0	1	0	0	0.99	0
M15	R04	47.3	65.1	76	95.3	98.2	98.2	0	1.11	0	1.01	1	1	0	1.01	0	0	1	0
M15	R05	39.7	55.1	61.3	91.1	100	100	0	0.93	0	0.94	0	0	0	0.94	0	0	0.94	0
M15	R06	41.7	64.1	69.1	94	100	100	0	0.9	0	0.93	0	0	0	0.93	0	0	0.93	0
M15	R07	41	67.9	74	95.3	100	100	0	0.91	0	0.93	0	0	0	0.93	0	0	0.93	0
M15	R08	38.1	59.4	66.4	93.6	100	100	0	1.04	0	1	0	1	0	1.01	0	0	1	0
M15	R09	54	62	80.2	87.6	99.9	100	0	0.97	0	1.02	0	0	0	1.02	0	0	1.02	0
M15	R10	72.8	75.3	82.5	94.7	99.1	99.1	0	0.89	0	0.91	1	0	0	0.91	0	0	0.91	1
M15	R11	71.2	73.1	80.4	93.5	98.9	98.9	0	0.91	0	0.94	1	0	0	0.94	0	0	0.94	1
M15	R12	69.7	73.7	81.3	93.7	100	100	0	0.9	0	0.92	0	1	0	0.93	0	0	0.92	1
M15	R13	55.5	73.5	80.1	92.3	99.5	99.5	0	1.08	0	1.08	1	1	0	1.08	0	0	1.08	0
M15	R14	52.5	61.2	79.1	88.8	96.9	96.9	0	1.02	0	1	1	1	0	1.01	0	0	1	1
M16	R01	18.8	51.5	40.3	83.3	93.6	100	0	0.76	0	0.88	0	1	0	0.88	0	0	0.88	0
M16	R02	29.6	53.9	54.1	95	99.5	100	0	0.88	0	0.98	0	0	0	0.98	0	0	0.98	0
M16	R03	22.9	58.4	50	91.6	94.6	100	0	0.81	0	0.92	0	1	0	0.92	0	0	0.92	0
M16	R04	8.9	51.5	34.1	92.4	96.8	100	0	0.82	0	0.9	0	1	0	0.9	0	0	0.91	0
M16	R05	15.9	43.1	34.2	84.7	92.8	100	0	0.81	0	0.91	1	1	0	0.91	0	0	0.91	0
M16	R06	19.3	46.4	33.8	80.1	96	100	0	0.88	0	0.93	0	2	0	0.93	0	0	0.93	0
M16	R07	19.8	53.6	37.5	85.8	98.4	99.3	0	0.86	0	0.89	1	1	0	0.9	0	0	0.89	0
M16	R08	20.8	54.6	48.2	92.3	97.6	100	0	0.87	0	0.95	0	1	0	0.96	0	0	0.95	0
M16	R09	21.2	50.5	48.1	88	98.7	100	0	0.9	0	0.95	0	1	0	0.95	0	0	0.95	0
M16	R10	24	54.7	52.5	92.6	98.7	100	0	0.92	0	0.99	0	1	0	0.99	0	0	0.99	0
M16	R11	46.5	71.8	76.6	98.6	100	100	0	1.07	0	1.08	0	0	0	1.09	0	0	1.08	0
M16	R12	19.1	45.3	44.5	83.9	91	100	0	0.79	0	0.9	0	1	0	0.9	0	0	0.92	1
M16	R13	89.6	89.6	89.6	100	100	100	0	0.81	0	0.87	0	0	0	0.87	0	0	0.87	0
M16	R14	21.2	73.7	57.6	100	98.8	100	0	0.89	0	0.98	0	1	0	0.99	0	0	0.98	0
M16	R15	21.7	64.2	56.9	97.9	99.9	100	0	0.87	0	0.95	0	0	0	0.95	0	0	0.95	0
M16	R16	22.8	67.1	59.1	98	100	100	0	0.89	0	0.94	0	1	0	0.95	0	0	0.94	0
M16	R17	18.2	52.6	41.4	89.2	90.8	100	0	0.82	0	0.94	0	1	0	0.94	0	0	0.95	0
M16	R18	17.5	54.1	43.6	91.3	95	100	0	0.86	0	0.96	0	1	0	0.96	0	0	0.96	0
M16	R19	16.4	52.2	39.2	89	90.9	100	0	0.82	0	0.94	0	1	0	0.94	0	0	0.94	0
M17	R01	15.3	32.5	30.3	77.4	90.5	100	0	0.95	0	1.02	1	1	0	1.01	0	0	1.02	0
M17	R02	11.8	26.8	23.6	74.1	88.7	100	0	0.92	0	0.99	1	1	0	0.98	0	0	1.01	0
M17	R03	22.6	54.2	50.8	94.9	98.2	100	0	0.84	0	0.97	0	1	0	0.97	0	0	0.97	0
M17	R04	24.1	43.9	47.2	86.5	98.9	100	0	0.91	0	0.97	0	1	0	0.97	0	0	0.97	0
M17	R05	23.4	42.4	45.8	85.2	98.2	99.9	0	0.98	0	1.02	1	1	0	1.02	0	0	1.02	0
M17	R06	26.7	57.6	55.4	91.9	99.8	100	0	0.97	0	0.99	0	1	0	1	0	0	1	0
M17	R07	28.3	55.6	56.2	91.9	99	100	0	1.06	0	1.07	0	1	0	1.08	0	0	1.07	0
M17	R08	17.2	38.6	33.6	86.6	95.6	100	0	0.96	0	1.02	1	1	0	1.02	0	0	1.03	0
M18	R01	100	100	100	100	100	100	0	1.02	0	1	0	0	0	1	0	0	1	0
M18	R02	100	100	100	100	100	100	0	1.06	0	1.02	0	0	0	1.02	0	0	1.02	0
M18	R03	100	100	100	100	100	100	0	1	0	1	0	0	0	1	0	0	1	0
M18	R04	100	100	100	100	100	100	0	1.01	0	1	0	0	0	1	0	0	1	0
M18	R05	67.3	90	96.9	99.8	100	100	0	1.09	0	1.07	0	0	0	1.07	0	0	1.07	0

Table B2 (continuation)

Position		General risk assessment						Specific risk assessment											
Museum	Room	Class AA	Class As	Class A	Class B	Class C	Class D	Paper Mould	Paper LM	Painting Mould	Painting LM	Painting Base	Painting Pict	Furniture Mould	Furniture LM	Furniture Base	Sculpture Mould	Sculpture LM	Sculpture Base
M18	R06	98.8	99.9	100	100	100	100	0	6.18	0	3.79	0	0	0	3.77	0	0	3.79	0
M18	R07	91.9	93.6	97.5	98.6	100	100	0	0.89	0	0.94	0	0	0	0.94	0	0	0.94	0
M18	R08	93.5	93.5	97.4	98.1	100	100	0	0.83	0	0.88	0	0	0	0.88	0	0	0.88	0
M18	R09	72.6	90.4	96.5	97.4	100	100	0	0.86	0	0.87	0	0	0	0.86	0	0	0.87	0
M19	R01	71.5	84.3	92.9	98	100	100	0	0.87	0	0.86	0	0	0	0.86	0	0	0.87	0
M19	R02	56.2	84.3	89.4	97.7	100	100	0	0.85	0	0.85	0	0	0	0.85	0	0	0.85	0
M19	R03	70.3	85.4	93.3	99.2	100	100	0	0.85	0	0.86	0	0	0	0.86	0	0	0.87	0
M19	R04	72.9	78.2	86.4	98.7	100	100	0	0.72	0	0.83	0	0	0	0.82	0	0	0.83	0
M19	R05	63.2	81.4	89.4	97.5	100	100	0	0.85	0	0.86	0	0	0	0.86	0	0	0.86	0
M19	R06	72.5	86.1	94.9	98.3	100	100	0	0.86	0	0.87	0	0	0	0.87	0	0	0.88	0
M19	R07	73.2	86.1	94.9	98.1	100	100	0	0.86	0	0.87	0	0	0	0.87	0	0	0.88	0
M19	R08	69.9	84.7	91.2	98	100	100	0	0.9	0	0.88	0	0	0	0.87	0	0	0.88	0
M19	R09	69.9	84.3	91.9	97.6	100	100	0	0.9	0	0.87	0	0	0	0.87	0	0	0.88	0
M19	R10	54.5	78.8	87.5	96.6	100	100	0	0.8	0	0.84	0	0	0	0.84	0	0	0.84	0
M20	R01	14.1	37.6	27.9	67	74.6	74.6	29	0.8	29	0.8	1	2	29	0.8	0	29	0.8	0
M20	R02	18.7	44.5	34	82.2	97.2	97.3	0	0.9	0	0.93	1	1	0	0.93	0	0	0.93	0
M20	R03	27.3	61.3	57.7	96.1	99.5	100	0	0.86	0	0.93	0	1	0	0.94	0	0	0.93	0
M20	R04	23.9	28.6	43	73.3	99.9	100	0	1.37	0	1.25	0	0	0	1.26	0	0	1.25	1
M20	R05	25.7	58.2	55.3	94.1	99.4	100	0	0.91	0	0.96	0	1	0	0.97	0	0	0.96	0
M20	R06	19.8	95.2	62.2	100	100	100	0	0.99	0	1.03	0	0	0	1.04	0	0	1.03	0
M20	R07	34.3	66.1	69.8	99.1	100	100	0	0.96	0	1.02	0	0	0	1.03	0	0	1.02	0
M20	R08	36.4	76	77.4	99.5	100	100	0	0.95	0	1.02	0	0	0	1.02	0	0	1.02	0
M20	R09	37.7	71.3	73.6	99.4	100	100	0	1.02	0	1.04	0	0	0	1.05	0	0	1.04	0
M20	R10	38.7	65.5	70.1	98.4	100	100	0	0.98	0	1.03	0	0	0	1.04	0	0	1.04	0
M20	R11	10.5	47.8	24.6	93.7	98.1	100	0	0.89	0	0.98	0	1	0	0.97	0	0	0.99	0
M21	R01	95.5	96.9	99.4	99.6	100	100	0	0.81	0	0.84	0	0	0	0.84	0	0	0.84	0
M21	R02	67	82.1	88.3	96.3	99.6	99.6	0	0.85	0	0.88	0	0	0	0.88	0	0	0.89	1
M21	R03	50.7	67.1	76.5	95.2	99.3	99.3	0	0.83	0	0.88	1	0	0	0.87	0	0	0.88	1
M21	R04	57.9	75.1	79.8	94.9	99.5	99.5	0	0.85	0	0.87	1	1	0	0.86	0	0	0.87	1
M21	R05	53.7	74.2	78.3	94	99.5	99.5	0	0.84	0	0.87	1	1	0	0.86	0	0	0.87	1
M21	R06	76.1	85.4	93.1	97	99.6	99.6	0	0.86	0	0.87	0	0	0	0.87	0	0	0.87	1
M21	R07	67.7	82.5	90.3	95.4	99.7	99.7	0	0.83	0	0.85	0	0	0	0.86	0	0	0.85	1
M21	R08	75.7	81.9	91.8	95.1	99.7	99.7	0	0.85	0	0.86	0	0	0	0.86	0	0	0.86	0
M21	R09	64.6	80.9	86.5	95.9	99.5	99.5	0	0.86	0	0.88	1	0	0	0.88	0	0	0.88	1
M21	R10	64.4	79.4	87.2	95.5	99.5	99.5	0	0.88	0	0.88	1	0	0	0.88	0	0	0.88	1
M21	R11	69.7	82	89.4	96.4	99.5	99.5	0	0.84	0	0.86	1	0	0	0.86	0	0	0.86	1
M21	R12	97.9	99.3	99.3	100	100	100	0	0.76	0	0.8	0	0	0	0.8	0	0	0.8	0
M21	R13	79.4	85.3	96.3	98.4	99.1	99.1	0	0.72	0	0.73	1	0	0	0.73	0	0	0.73	0
M21	R14	65.8	80	90.2	97.3	96.1	96.1	G?	0.75	G?	0.74	1	0	G?	0.74	0	G?	0.74	1
M21	R15	70.7	71.7	89.5	94.9	99.8	99.8	0	0.77	0	0.83	0	0	0	0.83	0	0	0.83	1
M21	R16	71.2	70.9	89.7	94.9	99.7	99.7	0	0.76	0	0.81	0	0	0	0.81	0	0	0.81	1
M21	R17	40.8	45.9	64.6	78.3	89.6	89.6	G?	0.94	G?	0.87	1	0	G?	0.87	0	G?	0.88	1
M21	R18	68.7	73.6	88.8	94.7	99.6	99.6	0	0.83	0	0.86	1	0	0	0.86	0	0	0.86	1
M21	R19	77.6	81.6	94.4	96.8	99.8	99.8	0	0.87	0	0.88	0	0	0	0.88	0	0	0.88	0
M21	R20	77.2	80	93	96.5	99.7	99.7	0	0.85	0	0.87	0	0	0	0.87	0	0	0.87	1
M21	R21	39.2	45.6	62.6	78.5	100	100	0	0.76	0	0.83	0	0	0	0.82	0	0	0.84	1
M21	R22	58.1	72.2	83.7	96.4	100	100	0	0.77	0	0.84	0	0	0	0.84	0	0	0.84	0

Table B2 (continuation)

Position		General risk assessment						Specific risk assessment											
Museum	Room	Class AA	Class As	Class A	Class B	Class C	Class D	Paper Mould	Paper LM	Painting Mould	Painting LM	Painting Base	Painting Pict	Furniture Mould	Furniture LM	Furniture Base	Sculpture Mould	Sculpture LM	Sculpture Base
M21	R23	82.9	91.1	94.2	97.9	99.9	99.9	0	1.02	0	0.99	0	0	0	0.99	0	0	0.99	0
M21	R24	42.3	69.1	72.2	93.8	99.8	99.8	0	1	0	1.01	0	0	0	1.01	0	0	1.01	1
M21	R25	91.1	95.1	97.4	98.8	100	100	0	1.02	0	0.98	0	0	0	0.98	0	0	0.98	0
M21	R26	74.9	80.9	88.1	97.3	99.6	99.6	0	1.03	0	0.98	0	0	0	0.98	0	0	0.98	1
M21	R27	89.4	95.5	97.5	99.3	100	100	0	0.92	0	0.92	0	0	0	0.92	0	0	0.92	0
M21	R28	81.8	86.8	93.6	98.6	100	100	0	1.03	0	0.99	0	0	0	0.99	0	0	0.99	0
M21	R29	61	85.7	89.1	99	100	100	0	0.99	0	0.97	0	0	0	0.97	0	0	0.97	0
M21	R30	21.1	36.9	39.2	80.1	99.3	99.4	0	1.12	0	1.08	0	1	0	1.07	0	0	1.09	1
M21	R31	85.9	90.5	97.5	99.1	100	100	0	0.77	0	0.83	0	0	0	0.83	0	0	0.83	0
M21	R32	75.8	87.8	95.7	98.6	99.7	99.7	0	0.76	0	0.79	1	0	0	0.8	0	0	0.79	0
M21	R33	47.6	52.1	74.7	88.5	99.8	99.8	0	1.09	0	1.05	1	0	0	1.05	0	0	1.05	1
M21	R34	56.2	64.8	83	96.4	99.9	99.9	0	0.73	0	0.79	0	0	0	0.78	0	0	0.79	0
M21	R35	68.2	75.8	87.6	96.4	99.9	99.9	0	0.75	0	0.82	0	0	0	0.81	0	0	0.82	1
M21	R36	78.4	78.5	89.9	98.3	99.8	99.8	0	0.79	0	0.8	0	0	0	0.8	0	0	0.8	0
M21	R37	50.7	67.1	76.5	95.2	99.3	99.3	0	0.83	0	0.88	1	0	0	0.87	0	0	0.88	1
M21	R38	65	81.8	88.1	97.8	99.7	99.7	0	0.89	0	0.91	1	0	0	0.91	0	0	0.91	1
M21	R39	71.2	79.6	90.3	97.8	99.9	99.9	0	0.91	0	0.93	0	0	0	0.92	0	0	0.93	0

Appendix C: Surface condition results

Table C1: Results for average surface conditions: Position & type, mathematical and climate class properties.

Position		Types					Statistical parameters												General risk assessment					
Museum	Room	QoE	LoC	Building Type	System Type	Position Type	T annual mean	T winter drop	T summer rise	dT hour	dT day	dT week	RH annual mean	R winter drop	R summer rise	dRH hour	dRH day	dRH week	Class AA	Class As	Class A	Class B	Class C	Class D
M04	R01s	2	2	1	2	5	20.08	1.6	2.1	0	0.3	0.9	35.8	3	4.1	0.5	5.8	12.1	72.3	88.5	95.4	95.6	100	100
M04	R04s	2	2	1	2	5	16.65	5.2	4.9	0.1	1.1	3.5	63.5	5.8	6.6	1	8.4	17.3	41.8	55.6	69	96.1	97.6	97.6
M04	R06s	2	3	1	3	5	19.45	4.7	4.5	0.9	9.1	15.7	56.9	5.2	8.8	2.7	24.3	38.7	33.5	40.7	51.6	79.2	97.8	98.8
M04	R07s	2	3	1	3	5	20.27	2.5	3.1	0.2	1.5	3.2	52.4	4.5	3.7	0.9	5.7	12.4	66.1	77.6	85.3	98.7	100	100
M04	R10s	2	2	1	2	5	17.39	5.1	4.8	0.5	6.4	11.1	56.7	19.7	6.6	1.6	16.8	30.7	27.2	34.2	44.3	78.4	98.7	98.7
M05	R01s	1	2	1	2	5	21.68	2.3	2	0.2	2	3.8	41.4	13	14.2	1.6	12.6	25.3	21.1	52.7	49	89.4	92.3	100
M05	R02s	1	1	1	1	5	14.38	4.3	4.8	0	0.3	1.2	66.3	2.7	4.6	0.8	6.5	16.7	66.4	72.2	91.8	96.9	94.7	94.7
M05	R03s	1	1	1	1	5	13.62	6.5	6.8	0	0.5	2	66.2	3.8	8	0.5	4.2	11.7	45.8	62.7	71.7	96.8	91.9	91.9
M05	R04s	1	1	1	1	5	13.33	4.9	4.7	0.1	0.7	2	71.5	5.2	6.1	1.3	9.8	24	43.7	49.5	75.6	84.3	62.7	62.7
M05	R05s	1	2	1	2	5	20.04	4.4	3.3	0.1	1.8	4.4	45.9	8.8	9.7	0.9	9.5	20.1	31.7	48.8	57.3	92.5	100	100
M05	R06s	1	1	1	1	5	14.74	6	6.3	0.1	1	2.6	64.3	2.9	5.4	0.8	6	14.8	58	66.5	80.2	97.2	97.7	97.7
M05	R07s	1	2	1	2	5	17.16	2.1	2.4	0.1	0.9	1.8	58.7	15	11.7	1.2	10.6	24.9	30.6	53.6	59.1	85.3	94	94
M05	R08s	1	1	1	1	5	13.77	7.7	7.9	0.5	5.7	10.2	69	11.5	14.4	1.8	16.6	29.4	14.2	27.5	28.9	77.9	63.8	63.8
M07	R07s	2	4	1	10	6	16.67	0.7	0.9	0.3	1.6	3	56.5	14.3	7.1	4.7	14.5	24	45	66.3	80.2	89.7	100	100
M07	R11s	2	4	1	10	6	19.91	1	1.2	0.3	2.4	4.3	46.2	8.5	3.6	1.4	8.8	17.2	72.6	78.6	89.3	95.5	99.6	100
M08	R04s	1	1	1	1	5	15.12	8.4	6.9	0.1	1.3	4.1	64.6	8.5	14.6	0.9	8.1	18.9	28.7	40.9	47.5	89	84.1	84.1
M08	R05s	1	1	1	1	5	15.29	8.3	6.9	0.2	2	4.8	63.9	8.3	15	0.9	6.8	17.1	28.9	42.4	47	90.8	86.1	86.1
M08	R06s	1	1	1	1	5	14.18	8.2	7.6	0.1	1.3	3.9	67.7	10.2	16.1	0.9	7.3	16.8	20.4	38.9	39.2	91.5	72.7	72.7
M08	R07s	1	1	1	1	5	15.25	8.7	7.4	0.2	2	4.7	63.4	9.6	14.5	0.7	5.8	14.4	19.8	43.3	43.6	93.9	86.8	86.8
M08	R08s	1	1	1	1	5	14.28	8.1	7.1	0.1	0.7	2.6	67.7	8	12.2	0.7	6.7	15.6	25.4	50.6	54.5	95.1	77.6	77.6
M08	R12s	1	1	1	1	5	11.64	6.9	6.8	0.3	3.5	6.8	80.1	5.5	10.1	1.9	17.7	29.1	28.9	32.9	50.8	74.6	28.4	28.4
M08	R15s	1	1	1	1	5	13.84	7.5	6.4	0.1	1	3.2	69.5	5.5	9.9	0.9	7.8	17.8	34.7	47.5	61.5	93.2	76.9	76.9
M09	R04s	1	1	1	1	5	16.41	6.1	6	0.2	2	5.8	60.3	7.2	6	0.8	6.3	16.8	34.2	53.1	61.3	94.1	100	100
M09	R05s	1	2	1	2	5	17.62	5.4	4.4	0.1	1.6	4.8	56	8.1	8.3	0.6	4	10.8	25.2	55.1	57.9	91.8	100	100
M09	R09s	1	1	1	1	5	12.34	7.7	7.8	0.2	3	7.3	79.5	15.3	13.2	1.1	9.7	18.6	15.1	38.2	32.6	85.5	36.7	36.7
M09	R10s	1	1	1	1	5	14.62	8.1	7.8	0.4	4.9	9.3	68	14.1	13.9	1	8	14.6	14.6	44.1	32.7	87.8	66.7	66.7
M10	R01s	1	4	2	10	5	20.05	2.4	2.4	1.1	8.3	14.6	52.6	3.8	4.1	3.1	20.4	34.4	37	45	60.9	83.4	98	99.9
M10	R03s	1	4	2	10	5	18.68	0.8	0.7	0.1	1.1	2.1	57.7	11	11.5	1.4	10.4	22	25.6	64.4	60.9	89.3	95.3	95.4
M10	R06s	1	4	2	10	5	18.76	1.5	1.8	0.2	2.7	4.5	56.7	5.6	5.8	1.2	11.4	22.9	53.6	59.2	77.5	89.7	99.7	99.7
M10	R07s	1	4	2	10	5	18.86	3.4	2.4	0.1	1.2	2.5	56.6	8.2	5.2	1.2	9.7	21.4	43.1	57.7	70.4	89	99.8	99.8
M10	R12s	1	4	2	10	5	17.16	2.4	2.5	0.1	0.7	2	63.2	4.7	2.9	1.7	11.6	24.1	54.5	57.1	86.2	88.9	96.8	96.8
M12	R15s	3	4	1	12	5	15.83	6.6	5	0.2	2	4.2	71.3	15	26.3	1	10	18.5	16.9	50.8	35	83.5	66.3	66.3
M12	R19s	3	4	1	12	5	15.86	7.2	5.5	0.2	2.1	4.4	73.7	18.2	30.2	1.2	11	20.6	13.5	38.2	27.5	71.3	61	61
M12	R28s	3	4	1	12	5	20.43	1.5	1.1	0.1	0.8	1.3	52.7	1.1	1.7	0.7	4.6	8.2	97.1	97.9	99.5	99.7	100	100
M14	R01s	2	2	1	7	5	20.29	2.8	2	0.6	6.3	10	44.1	7.3	5	1.7	17	29.4	34.3	43.6	63.5	83.4	97.5	100

Table C1 (continuation)

Position		Types					Statistical parameters												General risk assessment					
Museum	Room	QoE	LoC	Building Type	System Type	Position Type	T annual mean	T winter drop	T summer rise	dT hour	dT day	dT week	RH annual mean	R winter drop	R summer rise	dRH hour	dRH day	dRH week	Class AA	Class As	Class A	Class B	Class C	Class D
M14	R02s	2	4	1	12	5	21.49	1.2	0.8	0.3	3.2	5.5	48.1	1.5	1.9	1	8.7	15.9	90.7	91	92.3	97.7	100	100
M14	R05s	2	2	1	7	5	18.19	2.8	4.3	0.5	5.7	9.4	50.6	4.7	6.3	1.3	13.3	23.2	43.6	50.4	63.6	85.6	99.5	100
M14	R07s	2	2	1	7	5	21.07	3.1	1.9	0.8	10.1	16.7	50.6	5	6.5	2.4	23.7	37.6	19.4	38.8	42.6	81.6	97.2	100
M14	R13s	2	2	1	7	5	18.91	3.1	3.1	0.3	2.9	4.9	50.1	7.2	6.5	0.9	9.7	19	40.7	54.9	68.4	94	100	100
M15	R01s	1	4	2	10	5	16.45	3.2	3.4	0.1	0.9	2.4	63.3	4.7	3.9	1	6	13.2	54.2	60.6	82	92.3	95.5	95.5
M15	R02s	1	4	2	10	5	15.66	6.2	5.7	0.5	4.5	8	68.1	7.2	10.9	2.2	18.1	31	32.1	41.8	53.9	82.6	77.2	77.2
M15	R03s	1	4	2	10	5	15.45	4.3	4.6	0.3	3.6	6.9	67	3.5	8.3	1.9	16.2	27.7	33.7	37.7	54.3	79.3	81.6	81.6
M15	R04s	1	4	2	10	5	17.97	6.9	6	1.3	13.8	22.4	60.5	10.1	19.6	3.9	36.3	55.7	14	24	26	61.9	80.2	83.8
M15	R05s	1	4	2	10	5	17.47	5.6	5	0	0.5	2	61.2	3	6.2	0.6	5.5	13.3	63	74.1	83	94.7	97.5	97.5
M15	R06s	1	4	2	10	5	18.4	3.6	4.7	0.1	0.8	2.6	56.8	5.5	3.3	0.8	5.8	13.2	69.7	74.1	83.2	93.7	100	100
M15	R07s	1	4	2	10	5	17.02	5.6	5.2	0.1	1.1	3.2	62	4.5	9	0.8	5.9	13.8	47.1	66.2	76	97	97.1	97.1
M15	R08s	1	4	2	10	5	16.6	5	5.4	1.4	14.4	22.1	64.8	9.1	11.4	4.4	41.1	58.8	12.8	22.8	25.3	54.3	70.8	73.9
M15	R09s	1	4	2	10	5	17.53	6.4	6.2	1.3	13.7	20.7	58.6	10.7	16.5	4.1	38	57.8	11.7	18.9	23.5	55.5	84.4	87.6
M15	R10s	1	4	2	10	5	16.55	6.6	5.7	0.1	1.2	3.1	65.1	4.8	12.2	0.8	5.8	13.6	47.5	66.9	70.4	94.5	85.8	85.8
M15	R11s	1	4	2	10	5	18.63	5.7	5.3	0.1	0.8	2.6	55.2	3.1	5.7	0.7	5.9	13.7	62.2	71.3	80.4	93.3	98.4	98.4
M15	R12s	1	4	2	10	5	17.18	4.8	5.4	0.2	2	4.5	61.5	3.8	6	1	8	16.2	53.3	61.1	70.5	91.6	96	96
M16	R03s	1	2	2	2	5	19.68	2.4	2.2	0.1	1	2.2	50.2	8.3	9	0.8	6.7	14.4	44.6	67.9	72.6	95.8	99.8	99.8
M16	R06s	1	2	2	2	5	21.33	0.7	0.6	0.1	0.5	1.2	46.8	15.7	17.6	0.5	4	10	19.8	54.1	38.4	85.7	97.7	100
M16	R07s	1	2	2	2	5	20.09	1	1.1	0.1	1	2	52	17.3	18.5	0.8	6.3	14.8	19.4	45.8	36.2	81.2	94.1	94.8
M16	R10s	1	2	2	2	5	17.32	5.1	5.5	0.8	7.9	11.4	57	9.2	9.3	2.5	24.7	35.4	22.1	27.4	36.1	64.7	93.5	93.7
M16	R16s	1	2	2	2	5	17.43	3.9	4.5	0.1	1	3.1	58.4	9.1	9.4	0.6	4.9	11.5	36.5	66.9	66.9	96.8	100	100
M16	R17s	1	2	2	2	5	23.57	1.1	1.1	0.1	0.7	1.9	39.5	11.8	12.8	0.5	4.5	12.9	21.8	58.2	50.4	94.7	92.6	100
M16	R19s	1	2	2	2	5	17.5	1.6	2.1	0.3	3.6	6.4	57.1	14.8	16.4	1.4	13.7	24.2	8.9	36.7	26	74.9	84.5	84.5
M17	R03s	4	2	4	6	5	22.26	1.9	2.5	0.3	3	6.1	41.4	9.4	11.8	0.7	6.4	15.5	21.8	53.5	49.5	94.3	98.5	100
M17	R04s	4	2	4	6	5	19.82	2.4	2.8	0.3	3.4	6	48.8	9.3	10.9	1.3	11.3	24.4	23.8	40.6	47.8	83.5	99.6	100
M17	R07s	4	2	4	6	5	18.25	2.9	3	0.2	1.9	3.8	50.5	10.8	12.2	0.7	6.2	16.4	27.2	55.8	57.1	91.5	99.6	100
M18	R01s	4	4	4	12	5	19.42	0.6	0.7	0	0.2	0.5	52	2.2	1.9	0.4	1.6	3.2	99.7	100	100	100	100	100
M18	R02s	4	4	4	12	5	19.08	0.5	0.6	0	0.1	0.4	52.8	1.9	2.3	0.5	1.9	3.7	99.9	100	100	100	100	100
M18	R03s	4	4	4	12	5	19.83	0.3	0.5	0	0.2	0.4	50.7	1.5	0.9	0.3	1.4	2.8	99.8	100	100	100	100	100
M18	R04s	4	4	4	12	5	20.07	0.1	0.2	0	0.1	0.2	49.7	0.4	0.3	0.4	1.5	2.7	100	100	100	100	100	100
M18	R05s	4	4	4	12	5	20.1	0.4	0.5	0	0.1	0.4	47	5.1	5.8	0.8	4.9	11.1	66.3	89.5	96.8	99.7	100	100
M18	R06s	4	4	4	12	5	8.97	0.3	0.2	0	0.3	0.6	42.7	2	4	0.3	1.4	3.1	99.6	100	100	100	100	100
M18	R07s	4	4	4	12	5	21.47	0.2	0.3	0.1	0.4	0.8	46.7	2.3	1.5	0.8	3.7	7.6	92.8	94	97.8	98.9	100	100
M18	R08s	4	4	4	12	5	21.18	0.7	0.5	0.1	0.5	1	50.5	1.6	2.9	0.9	4	8.4	93.7	94.6	98.4	98.2	100	100
M18	R09s	4	4	4	12	5	16.68	3.3	3.5	0.5	5.9	10.3	70.5	17.5	18.8	2.6	22.7	39.6	9.5	30.7	22.6	63.6	57.5	57.6
M20	R01s	1	2	1	2	5	20.51	0.6	0.5	0	0.1	0.2	56.9	18.5	21.5	0.4	3.8	11.1	14.3	38.8	28.8	68.4	76.7	76.7
M20	R02s	1	2	1	2	5	20.83	0.9	1	1.5	20.7	31.3	48.1	13.9	17.6	2.6	30.1	42.7	21.8	49.8	39.5	82	96.2	97.7
M20	R03s	1	2	1	2	5	19.01	2.9	2.4	0	0.3	1.1	52.9	11.1	11.2	0.7	7.1	18.2	31.9	54	59.8	88.2	99.7	99.7
M20	R05s	1	2	1	2	5	16.47	5.5	5	0.4	4.8	8.6	60.7	9.9	6.2	1.6	15.2	26.3	31.5	39.9	51.6	82.9	98.2	98.2
M20	R09s	1	2	1	2	5	16.92	5.1	4.9	0	0.6	2.4	55.9	6.9	5.8	0.5	5.5	13.4	48.1	63.8	73.9	97.6	100	100
M20	R10s	1	2	1	2	5	18.37	5	5.2	0.3	2.9	5.7	50.8	5.4	6	0.8	7.1	15.4	50.2	65.9	72.7	96.6	100	100
M20	R11s	1	2	1	2	5	22.28	2.9	1.6	0.2	1.9	4.3	42	13.8	13.9	0.7	4.9	12.2	10.6	47.5	24.5	93.5	95.5	100
M21	R05s	4	4	3	12	5	20.82	0.7	1.7	0.3	1.2	2.1	52.5	14.8	7.4	1.3	7.3	15.3	54.1	73.9	78.3	93.9	99.5	99.5
M21	R06s	4	4	3	12	5	19.94	0.9	0.6	0.1	0.9	1.7	55.8	4.1	3.2	1.4	6.9	14.2	80.9	85.9	94.1	97.2	99.6	99.6
M21	R07s	4	4	3	12	5	20.71	3.8	2.6	0.2	1.5	2.6	54.4	12.6	12	1.7	8.7	16.3	34.6	76.5	63.5	95	99.9	99.9
M21	R08s	4	4	3	12	5	20.15	1.1	0.6	0.2	1.2	2.3	55.4	4.9	2.9	1.5	7.8	15.2	76.2	82.6	92.1	95.2	99.8	99.8
M21	R09s	4	4	3	12	5	20.52	0.6	0.6	0.3	1.3	2.1	53.2	5.8	6.7	1.6	8	15.9	65.5	81.5	87.1	96.1	99.5	99.5

Table C1 (continuation)

Position		Types					Statistical parameters												General risk assessment					
Museum	Room	QoE	LoC	Building Type	System Type	Position Type	T annual mean	T winter drop	T summer rise	dT hour	dT day	dT week	RH annual mean	R winter drop	R summer rise	dRH hour	dRH day	dRH week	Class AA	Class As	Class A	Class B	Class C	Class D
M21	R10s	4	4	3	12	5	20.11	0.6	0.6	0.4	1.7	2.6	54.5	6.1	6.5	1.9	8.8	16.9	64.2	79.4	86.9	95.5	99.4	99.4
M21	R13s	4	4	3	12	5	20.37	0.5	0.5	0.2	1.4	2.2	61.9	3.4	3.9	1.3	6.7	13.3	78.4	85.2	95.9	98.3	99.2	99.2
M21	R14s	4	4	3	12	5	20.03	0.5	0.5	0.2	1.3	2.1	62.9	6.4	5.9	1.9	8.6	16	66.7	80.4	90.6	97.5	97.1	97.1
M21	R19s	4	4	3	12	5	20.55	0.6	0.6	0.2	1.3	2.1	52.7	3.4	3.8	1.4	7.6	15	77.6	82.2	94.6	97	99.9	99.9
M21	R20s	4	4	3	12	5	20.73	0.7	0.7	0.2	1.7	2.5	52.7	3.7	3.6	1.4	8.1	15.2	77.2	80.8	93.2	96.8	99.9	99.9
M21	R24s	4	4	4	12	6	20.08	1.3	2.2	1.3	3.1	4.6	49.6	8.9	8.6	5.4	16.3	25.5	39.3	66.9	67.9	93	99.7	99.7
M21	R26s	4	4	4	12	6	18.94	1.2	1.4	1.4	4	5.9	55.2	5.8	7.6	5.4	16.2	24.2	58.3	64.9	73.4	91.1	98.4	98.4
M21	R28s	4	4	4	12	6	18.85	0.7	1.1	0.4	1.7	3.6	54.9	3.8	4.1	2.5	10.2	18.6	73.8	80.3	89.8	95.5	100	100
M21	R30s	4	4	4	12	6	19.35	1.9	2.5	1.5	5.1	7.7	49.7	10	11.9	5.1	19.4	31.8	19.1	32.8	35	76.5	98.4	98.6
M21	R33s	4	4	4	12	5	19.02	2	2.4	0.1	1.2	2.4	50.6	8.3	6.8	1.4	10.1	21.3	50.5	55.5	77.5	89.6	99.8	99.8
M21	R38s	4	4	4	12	5	20.84	0.3	0.2	0.5	1	1.5	50.3	5.7	7.2	1.7	7.2	14.5	65.1	80.9	87.7	97.7	99.7	99.7

Table C2: Results for average surface conditions: Position, climate class propertie and object risk assessment.s

Position		General risk assessment						Specific risk assessment											
Museum	Room	Class AA	Class As	Class A	Class B	Class C	Class D	Paper Mould	Paper LM	Painting Mould	Painting LM	Painting Base	Painting Pict	Furniture Mould	Furniture LM	Furniture Base	Sculpture Mould	Sculpture LM	Sculpture Base
M04	R01s	72.3	88.5	95.4	95.6	100	100	0	1.52	0	1.53	0	0	0	1.54	0	0	1.53	0
M04	R04s	41.8	55.6	69	96.1	97.6	97.6	0	1.04	0	0.96	1	0	0	0.97	0	0	0.96	1
M04	R06s	33.5	40.7	51.6	79.2	97.8	98.8	0	0.84	0	0.82	1	0	0	0.81	0	0	0.85	1
M04	R07s	66.1	77.6	85.3	98.7	100	100	0	0.84	0	0.88	0	0	0	0.89	0	0	0.88	0
M04	R10s	27.2	34.2	44.3	78.4	98.7	98.7	0	0.96	0	1.05	1	0	0	1.05	0	0	1.07	1
M05	R01s	21.1	52.7	49	89.4	92.3	100	0	0.95	0	1.04	0	1	0	1.06	0	0	1.04	0
M05	R02s	66.4	72.2	91.8	96.9	94.7	94.7	0	1.32	0	1.12	1	0	0	1.12	0	0	1.12	0
M05	R03s	45.8	62.7	71.7	96.8	91.9	91.9	0	1.35	0	1.18	1	0	0	1.18	0	0	1.18	0
M05	R04s	43.7	49.5	75.6	84.3	62.7	62.7	G?	1.35	G?	1.11	1	0	G?	1.11	0	G?	1.11	1
M05	R05s	31.7	48.8	57.3	92.5	100	100	0	0.98	0	1.03	0	0	0	1.04	0	0	1.04	0
M05	R06s	58	66.5	80.2	97.2	97.7	97.7	0	1.23	0	1.1	1	0	0	1.1	0	0	1.1	0
M05	R07s	30.6	53.6	59.1	85.3	94	94	0	1.12	0	1.02	1	1	0	1.03	0	0	1.02	1
M05	R08s	14.2	27.5	28.9	77.9	63.8	63.8	G?	1.22	G?	1.09	1	1	G?	1.08	0	G?	1.1	1
M07	R07s	45	66.3	80.2	89.7	100	100	0	1.36	0	1.19	0	1	0	1.19	0	0	1.19	1
M07	R11s	72.6	78.6	89.3	95.5	99.6	100	0	1.1	0	1.11	0	0	0	1.11	0	0	1.1	0
M08	R04s	28.7	40.9	47.5	89	84.1	84.1	5	1.18	5	1.07	1	1	5	1.07	0	5	1.07	1
M08	R05s	28.9	42.4	47	90.8	86.1	86.1	G?	1.16	G?	1.06	1	1	G?	1.06	0	G?	1.06	1
M08	R06s	20.4	38.9	39.2	91.5	72.7	72.7	11	1.21	11	1.1	1	1	11	1.09	1	11	1.1	1
M08	R07s	19.8	43.3	43.6	93.9	86.8	86.8	G?	1.13	G?	1.07	1	1	G?	1.07	0	G?	1.07	0
M08	R08s	25.4	50.6	54.5	95.1	77.6	77.6	0	1.21	0	1.08	1	0	0	1.08	0	0	1.08	1
M08	R12s	28.9	32.9	50.8	74.6	28.4	28.4	83	1.41	83	1.12	1	0	83	1.11	0	83	1.13	1
M08	R15s	34.7	47.5	61.5	93.2	76.9	76.9	0	1.25	0	1.09	1	0	0	1.09	0	0	1.09	0
M09	R04s	34.2	53.1	61.3	94.1	100	100	0	1.05	0	1.01	1	0	0	1.02	0	0	1.01	0
M09	R05s	25.2	55.1	57.9	91.8	100	100	0	1.04	0	1.02	0	0	0	1.02	0	0	1.02	0
M09	R09s	15.1	38.2	32.6	85.5	36.7	36.7	105	1.25	105	1.06	1	1	105	1.05	0	105	1.06	1
M09	R10s	14.6	44.1	32.7	87.8	66.7	66.7	G?	1.1	G?	1.03	1	1	G?	1.03	0	G?	1.04	0

Table C2 (continuation)

Position		General risk assessment						Specific risk assessment											
Museum	Room	Class AA	Class As	Class A	Class B	Class C	Class D	Paper Mould	Paper LM	Painting Mould	Painting LM	Painting Base	Painting Pict	Furniture Mould	Furniture LM	Furniture Base	Sculpture Mould	Sculpture LM	Sculpture Base
M10	R01s	37	45	60.9	83.4	98	99.9	0	0.89	0	0.87	0	0	0	0.87	0	0	0.89	1
M10	R03s	25.6	64.4	60.9	89.3	95.3	95.4	G?	0.99	G?	0.94	1	1	G?	0.93	0	G?	0.94	1
M10	R06s	53.6	59.2	77.5	89.7	99.7	99.7	0	0.98	0	0.94	0	0	0	0.94	0	0	0.94	1
M10	R07s	43.1	57.7	70.4	89	99.8	99.8	G?	0.96	G?	0.93	0	0	G?	0.93	0	G?	0.93	1
M10	R12s	54.5	57.1	86.2	88.9	96.8	96.8	G?	1.05	G?	0.96	1	0	G?	0.96	0	G?	0.96	1
M12	R15s	16.9	50.8	35	83.5	66.3	66.3	201	1.11	201	0.97	1	2	201	0.96	1	201	0.97	1
M12	R19s	13.5	38.2	27.5	71.3	61	61	287	1.07	287	0.94	1	2	287	0.92	1	287	0.94	1
M12	R28s	97.1	97.9	99.5	99.7	100	100	0	0.87	0	0.89	0	0	0	0.89	0	0	0.89	0
M14	R01s	34.3	43.6	63.5	83.4	97.5	100	0	1.08	0	1.08	0	0	0	1.08	0	0	1.1	0
M14	R02s	90.7	91	92.3	97.7	100	100	0	0.85	0	0.9	0	0	0	0.9	0	0	0.91	0
M14	R05s	43.6	50.4	63.6	85.6	99.5	100	0	1.17	0	1.1	0	0	0	1.11	0	0	1.12	1
M14	R07s	19.4	38.8	42.6	81.6	97.2	100	0	0.84	0	0.83	0	0	0	0.82	0	0	0.87	1
M14	R13s	40.7	54.9	68.4	94	100	100	0	1.06	0	1.05	0	0	0	1.06	0	0	1.05	0
M15	R01s	54.2	60.6	82	92.3	95.5	95.5	0	1.14	0	1.01	1	0	0	1.01	0	0	1.01	0
M15	R02s	32.1	41.8	53.9	82.6	77.2	77.2	G?	1.09	G?	0.97	1	0	G?	0.97	0	G?	0.98	1
M15	R03s	33.7	37.7	54.3	79.3	81.6	81.6	0	1.19	0	1.03	1	0	0	1.03	0	0	1.04	1
M15	R04s	14	24	26	61.9	80.2	83.8	40	0.95	40	0.83	1	1	40	0.83	1	40	0.89	1
M15	R05s	63	74.1	83	94.7	97.5	97.5	G?	0.96	G?	0.93	1	0	G?	0.93	0	G?	0.93	1
M15	R06s	69.7	74.1	83.2	93.7	100	100	0	0.94	0	0.93	1	0	0	0.94	0	0	0.93	1
M15	R07s	47.1	66.2	76	97	97.1	97.1	0	1.02	0	0.96	1	0	0	0.96	0	0	0.96	0
M15	R08s	12.8	22.8	25.3	54.3	70.8	73.9	G?	1.06	G?	0.86	1	1	G?	0.86	0	G?	0.92	1
M15	R09s	11.7	18.9	23.5	55.5	84.4	87.6	60	1.07	60	0.92	1	1	60	0.91	1	60	0.98	1
M15	R10s	47.5	66.9	70.4	94.5	85.8	85.8	G?	0.99	G?	0.94	1	0	G?	0.94	0	G?	0.94	1
M15	R11s	62.2	71.3	80.4	93.3	98.4	98.4	0	0.93	0	0.94	1	0	0	0.94	0	0	0.94	1
M15	R12s	53.3	61.1	70.5	91.6	96	96	0	0.99	0	0.95	1	0	0	0.95	0	0	0.95	1
M16	R03s	44.6	67.9	72.6	95.8	99.8	99.8	0	0.96	0	0.97	1	0	0	0.97	0	0	0.97	0
M16	R06s	19.8	54.1	38.4	85.7	97.7	100	0	0.87	0	0.92	0	1	0	0.92	0	0	0.92	0
M16	R07s	19.4	45.8	36.2	81.2	94.1	94.8	G?	0.89	G?	0.9	1	2	G?	0.9	0	G?	0.9	0
M16	R10s	22.1	27.4	36.1	64.7	93.5	93.7	0	1.04	0	0.97	1	0	0	0.97	0	0	1	1
M16	R16s	36.5	66.9	66.9	96.8	100	100	0	1.03	0	0.99	0	0	0	1	0	0	0.99	0
M16	R17s	21.8	58.2	50.4	94.7	92.6	100	0	0.8	0	0.94	0	1	0	0.94	0	0	0.94	0
M16	R19s	8.9	36.7	26	74.9	84.5	84.5	G?	1.11	G?	1.02	1	1	G?	1.03	0	G?	1.03	1
M17	R03s	21.8	53.5	49.5	94.3	98.5	100	0	0.86	0	0.97	0	1	0	0.98	0	0	0.97	0
M17	R04s	23.8	40.6	47.8	83.5	99.6	100	0	0.95	0	0.98	0	1	0	0.98	0	0	0.98	0
M17	R07s	27.2	55.8	57.1	91.5	99.6	100	0	1.12	0	1.09	1	1	0	1.1	0	0	1.09	0
M18	R01s	99.7	100	100	100	100	100	0	1.03	0	1.01	0	0	0	1.01	0	0	1.01	0
M18	R02s	99.9	100	100	100	100	100	0	1.06	0	1.02	0	0	0	1.02	0	0	1.02	0
M18	R03s	99.8	100	100	100	100	100	0	1.01	0	1	0	0	0	1	0	0	1	0
M18	R04s	100	100	100	100	100	100	0	1	0	1	0	0	0	1	0	0	1	0
M18	R05s	66.3	89.5	96.8	99.7	100	100	0	1.06	0	1.07	0	0	0	1.07	0	0	1.07	0
M18	R06s	99.6	100	100	100	100	100	0	6.11	0	3.77	0	0	0	3.76	0	0	3.78	0
M18	R07s	92.8	94	97.8	98.9	100	100	0	0.89	0	0.94	0	0	0	0.94	0	0	0.94	0
M18	R08s	93.7	94.6	98.4	98.2	100	100	0	0.84	0	0.88	0	0	0	0.88	0	0	0.88	0
M18	R09s	9.5	30.7	22.6	63.6	57.5	57.6	240	1.05	240	0.9	1	2	240	0.89	1	240	0.91	1
M20	R01s	14.3	38.8	28.8	68.4	76.7	76.7	16	0.79	16	0.8	1	2	16	0.8	0	16	0.8	0
M20	R02s	21.8	49.8	39.5	82	96.2	97.7	0	0.88	0	0.84	1	1	0	0.84	0	0	0.85	0
M20	R03s	31.9	54	59.8	88.2	99.7	99.7	0	0.98	0	0.97	1	1	0	0.98	0	0	0.97	0

Table C2 (continuation)

Position		General risk assessment						Specific risk assessment											
Museum	Room	Class AA	Class As	Class A	Class B	Class C	Class D	Paper Mould	Paper LM	Painting Mould	Painting LM	Painting Base	Painting Pict	Furniture Mould	Furniture LM	Furniture Base	Sculpture Mould	Sculpture LM	Sculpture Base
M20	R05s	31.5	39.9	51.6	82.9	98.2	98.2	0	1.07	0	0.99	1	0	0	1	0	0	1	1
M20	R09s	48.1	63.8	73.9	97.6	100	100	0	1.12	0	1.07	0	0	0	1.08	0	0	1.07	0
M20	R10s	50.2	65.9	72.7	96.6	100	100	0	1.04	0	1.05	0	0	0	1.06	0	0	1.06	0
M20	R11s	10.6	47.5	24.5	93.5	95.5	100	0	0.87	0	0.98	0	1	0	0.96	0	0	0.98	0
M21	R05s	54.1	73.9	78.3	93.9	99.5	99.5	0	0.84	0	0.87	1	1	0	0.86	0	0	0.87	1
M21	R06s	80.9	85.9	94.1	97.2	99.6	99.6	0	0.87	0	0.87	0	0	0	0.87	0	0	0.87	0
M21	R07s	34.6	76.5	63.5	95	99.9	99.9	0	0.81	0	0.85	0	1	0	0.86	0	0	0.84	0
M21	R08s	76.2	82.6	92.1	95.2	99.8	99.8	0	0.85	0	0.86	0	0	0	0.86	0	0	0.86	0
M21	R09s	65.5	81.5	87.1	96.1	99.5	99.5	0	0.86	0	0.88	1	0	0	0.87	0	0	0.88	1
M21	R10s	64.2	79.4	86.9	95.5	99.4	99.4	0	0.88	0	0.88	1	0	0	0.88	0	0	0.88	1
M21	R13s	78.4	85.2	95.9	98.3	99.2	99.2	0	0.71	0	0.73	1	0	0	0.73	0	0	0.73	0
M21	R14s	66.7	80.4	90.6	97.5	97.1	97.1	0	0.74	0	0.74	1	0	0	0.74	0	0	0.74	1
M21	R19s	77.6	82.2	94.6	97	99.9	99.9	0	0.86	0	0.88	0	0	0	0.88	0	0	0.88	0
M21	R20s	77.2	80.8	93.2	96.8	99.9	99.9	0	0.84	0	0.86	0	0	0	0.87	0	0	0.87	0
M21	R24s	39.3	66.9	67.9	93	99.7	99.7	0	1.01	0	1.01	0	0	0	1.01	0	0	1.01	1
M21	R26s	58.3	64.9	73.4	91.1	98.4	98.4	0	1.02	0	0.97	1	0	0	0.97	0	0	0.98	0
M21	R28s	73.8	80.3	89.8	95.5	100	100	0	1.03	0	0.99	0	0	0	0.98	0	0	0.99	0
M21	R30s	19.1	32.8	35	76.5	98.4	98.6	0	1.12	0	1.08	1	1	0	1.07	0	0	1.09	1
M21	R33s	50.5	55.5	77.5	89.6	99.8	99.8	0	1.06	0	1.04	1	0	0	1.04	0	0	1.04	0
M21	R38s	65.1	80.9	87.7	97.7	99.7	99.7	0	0.88	0	0.91	0	0	0	0.91	0	0	0.91	1
M20	R05s	31.5	39.9	51.6	82.9	98.2	98.2	0	1.07	0	0.99	1	0	0	1	0	0	1	1
M20	R09s	48.1	63.8	73.9	97.6	100	100	0	1.12	0	1.07	0	0	0	1.08	0	0	1.07	0

Appendix D: simulation model

See Nomenclature for an explanation of abbreviations and units

1. GENERAL PARAMETERS

General

Parameter	Description
Building function type	Standard museum exhibition room, 16 zones, each zone is a combination of QoE and LoC
Number of visitors per year	10220
Average length of visit	1h
Sort of visits	Free tour

2. CONSTRUCTION SPECIFICATION

Walls

ID	Description	Ri	d1	matID	d2	matID	d3	matID	d4	matID	Re	ab	eb
1	Brick wall	0.13	0.01	362	0.4	234					0.04	0.5	0.9
2	Brick wall	0.13	0.01	362	0.4	234					0.04	0.5	0.9
3	Brick wall insulated	0.13	0.01	362	0.1	408	0.4	234			0.04	0.5	0.9
4	New brick wall	0.13	0.01	362	0.1	234	0.15	408	0.1	234	0.04	0.5	0.9

Floors

ID	Description	Ri	d1	matID	d2	matID	d3	matID	d4	matID	Re	ab	eb
5	Stone floor	0.10	0.01	362	0.1	234					0.1	0.5	0.9

Ceiling

ID	Description	Ri	d1	matID	d2	matID	d3	matID	d4	matID	Re	ab	eb
6	Stone ceiling	0.10	0.01	362	0.1	234					0.1	0.5	0.9

Glazing

ID	Description	Uglas	CFr	ZTA	ZTAw	CFrw	Uglasw
1	Single glazing	5.7	0.01	0.80	0.31	0.34	5.7
2	Double glazing	3.2	0.03	0.70	0.36	0.36	3.2
3	Low-e glazing	1.4	0.03	0.65	0.30	0.40	1.4
4	Saint Rock skn 165	1.309	0.047	0.308	0.072	0.116	1.309

3. ROOM OR ZONE SPECIFICATION

Volume

ID	Description	Vol	Infil	Heat	Cool	Hum	Deh	CFh	CFs	CFi	eww	Tww	fbv	CFz
1	Room QoE 1 & LoC 1	350	1.0	0	0	0	0	0.8	0.8	0.5	0	22	30	1
2	Room QoE 1 & LoC 2	350	1.0	5e3	0	0	0	0.8	0.8	0.5	0	22	30	1
3	Room QoE 1 & LoC 3	350	1.0	5e3	0	1e-4	1e-4	0.8	0.8	0.5	0	22	30	1
4	Room QoE 1 & LoC 4	350	1.0	1e4	1e4	2e-4	2e-4	1	0.8	0.5	0	22	30	1
5	Room QoE 2 & LoC 1	350	0.4	0	0	0	0	0.8	0.8	0.5	0	22	30	1
6	Room QoE 2 & LoC 2	350	0.4	5e3	0	0	0	0.8	0.8	0.5	0	22	30	1
7	Room QoE 2 & LoC 3	350	0.4	5e3	0	1e-4	1e-4	0.8	0.8	0.5	0	22	30	1
8	Room QoE 2 & LoC 4	350	0.4	1e4	1e4	2e-4	2e-4	1	0.8	0.5	0	22	30	1
9	Room QoE 3 & LoC 1	350	0.2	0	0	0	0	0.8	0.8	0.5	0	22	30	1
10	Room QoE 3 & LoC 2	350	0.2	5e3	0	0	0	0.8	0.8	0.5	0	22	30	1
11	Room QoE 3 & LoC 3	350	0.2	5e3	0	1e-4	1e-4	0.8	0.8	0.5	0	22	30	1
12	Room QoE 3 & LoC 4	350	0.2	1e4	1e4	2e-4	2e-4	1	0.8	0.5	0	22	30	1
13	Room QoE 4 & LoC 1	350	0.1	0	0	0	0	0.8	0.8	0.5	0	22	30	1
14	Room QoE 4 & LoC 2	350	0.1	5e3	0	0	0	0.8	0.8	0.5	0	22	30	1
15	Room QoE 4 & LoC 3	350	0.1	5e3	0	1e-4	1e-4	0.8	0.8	0.5	0	22	30	1
16	Room QoE 4 & LoC 4	350	0.1	1e4	1e4	2e-4	2e-4	1	0.8	0.5	0	22	30	1

Envelope

ID	Description	VolID	Surface [m2]	WallID	% glazing	GlasID	Beta [°]	Gamma [°]	Bridge
1	South wall zone 1	1	35	1	14.29	1	90	0	0
2	West wall zone 1	1	35	1	14.29	1	90	90	0
3	South wall zone 2	2	35	1	14.29	1	90	0	0
4	West wall zone 2	2	35	1	14.29	1	90	90	0
5	South wall zone 3	3	35	1	14.29	1	90	0	0
6	West wall zone 3	3	35	1	14.29	1	90	90	0
7	South wall zone 4	4	35	1	14.29	1	90	0	0
8	West wall zone 4	4	35	1	14.29	1	90	90	0
9	South wall zone 5	5	35	2	14.29	2	90	0	0
10	West wall zone 5	5	35	2	14.29	2	90	90	0
11	South wall zone 6	6	35	2	14.29	2	90	0	0
12	West wall zone 6	6	35	2	14.29	2	90	90	0
13	South wall zone 7	7	35	2	14.29	2	90	0	0
14	West wall zone 7	7	35	2	14.29	2	90	90	0
15	South wall zone 8	8	35	2	14.29	2	90	0	0
16	West wall zone 8	8	35	2	14.29	2	90	90	0
17	South wall zone 9	9	35	3	14.29	3	90	0	0
18	West wall zone 9	9	35	3	14.29	3	90	90	0
19	South wall zone 10	10	35	3	14.29	3	90	0	0
20	West wall zone 10	10	35	3	14.29	3	90	90	0
21	South wall zone 11	11	35	3	14.29	3	90	0	0
22	West wall zone 11	11	35	3	14.29	3	90	90	0
23	South wall zone 12	12	35	3	14.29	3	90	0	0
24	West wall zone 12	12	35	3	14.29	3	90	90	0
25	South wall zone 13	13	35	4	14.29	4	90	0	0
26	West wall zone 13	13	35	4	14.29	4	90	90	0
27	South wall zone 14	14	35	4	14.29	4	90	0	0
28	West wall zone 14	14	35	4	14.29	4	90	90	0
29	South wall zone 15	15	35	4	14.29	4	90	0	0
30	West wall zone 15	15	35	4	14.29	4	90	90	0
31	South wall zone 16	16	35	4	14.29	4	90	0	0
32	West wall zone 16	16	35	4	14.29	4	90	90	0

Adiabatic walls

ID	Description	VolID	Surface [m2]	WallID

1	Interior wall	1	70	5
2	Interior floor and ceiling	1	200	6
3	Interior wall	2	70	5
4	Interior floor and ceiling	2	200	6
5	Interior wall	3	70	5
6	Interior floor and ceiling	3	200	6
7	Interior wall	4	70	5
8	Interior floor and ceiling	4	200	6
9	Interior wall	5	70	5
10	Interior floor and ceiling	5	200	6
11	Interior wall	6	70	5
12	Interior floor and ceiling	6	200	6
13	Interior wall	7	70	5
14	Interior floor and ceiling	7	200	6
15	Interior wall	8	70	5
16	Interior floor and ceiling	8	200	6
17	Interior wall	9	70	5
18	Interior floor and ceiling	9	200	6
19	Interior wall	10	70	5
20	Interior floor and ceiling	10	200	6
21	Interior wall	11	70	5
22	Interior floor and ceiling	11	200	6
23	Interior wall	12	70	5
24	Interior floor and ceiling	12	200	6
25	Interior wall	13	70	5
26	Interior floor and ceiling	13	200	6
27	Interior wall	14	70	5
28	Interior floor and ceiling	14	200	6
29	Interior wall	15	70	5
30	Interior floor and ceiling	15	200	6
31	Interior wall	16	70	5
32	Interior floor and ceiling	16	200	6

4. USE

Use

Day	Opening (staff)	Closing (staff)	Opening (visitors)	Closing (visitors)	Staff	Visitors	Duration
Monday	10:00	17:00	10:00	17:00	1	4	Continuous
Tuesday	10:00	17:00	10:00	17:00	1	4	Continuous
Wednesday	10:00	17:00	10:00	17:00	1	4	Continuous
Thursday	10:00	17:00	10:00	17:00	1	4	Continuous
Friday	10:00	17:00	10:00	17:00	1	4	Continuous
Saturday	10:00	17:00	10:00	17:00	1	4	Continuous
Sunday	10:00	17:00	10:00	17:00	1	4	Continuous

5. CONTROL

Ventilation between zones

VolID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Set points and power per zone

VolID	Ers	vvmino	vvminc	vvmaxo	vvmaxc	Tfc	Qinto	Qintc	Ginto	Gintc	Th	Tc	RHh	RHd
1	300	1.0	1.0	1.0	1.0	30	500	0	1e-5	0	0	100	0	100
2	300	1.0	1.0	1.0	1.0	30	500	0	1e-5	0	20	100	0	100
3	300	1.0	1.0	1.0	1.0	30	500	0	1e-5	0	20	100	40	60
4	300	1.0	1.0	1.0	1.0	30	500	0	1e-5	0	20	22	48	52
5	300	0.4	0.4	0.4	0.4	30	500	0	1e-5	0	0	100	0	100
6	300	0.4	0.4	0.4	0.4	30	500	0	1e-5	0	20	100	0	100
7	300	0.4	0.4	0.4	0.4	30	500	0	1e-5	0	20	100	40	60
8	300	0.4	0.4	0.4	0.4	30	500	0	1e-5	0	20	22	48	52
9	300	0.2	0.2	0.2	0.2	30	500	0	1e-5	0	0	100	0	100
10	300	0.2	0.2	0.2	0.2	30	500	0	1e-5	0	20	100	0	100
11	300	0.2	0.2	0.2	0.2	30	500	0	1e-5	0	20	100	40	60
12	300	0.2	0.2	0.2	0.2	30	500	0	1e-5	0	20	22	48	52
13	300	0.1	0.1	0.1	0.1	30	500	0	1e-5	0	0	100	0	100
14	300	0.1	0.1	0.1	0.1	30	500	0	1e-5	0	20	100	0	100
15	300	0.1	0.1	0.1	0.1	30	500	0	1e-5	0	20	100	40	60
16	300	0.1	0.1	0.1	0.1	30	500	0	1e-5	0	20	22	48	52

6. VARIANTS

Variants

Variant number	Description
1	Basic case
2	Wall thickness + 10%
3	Exterior surface area + 10%
4	Glazing surface area + 10%
5	Interior surface area + 10%
6	Ventilation rate + 10%
7	Sun blinds (Ers 100 instead of 300, ZTA = 0.1/0.05)
8	More visitors (+10%)
9	T set point - 1°C
10	T set point + 1°C
11	RH set point – 5%
12	RH set point + 5%
13	Set point T based on sine curve (T +/- 2°C)
14	Set point RH based on sine curve (RH +/- 10%)
15	Set point T and RH based on sine curves (T +/- 2°C, RH +/- 10%)
16	Set point T based on outdoor temperature
17	Set point T based on outdoor temperature, Set point RH based on sine curve (RH +/- 10%)

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