Cultural Heritage Science

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# Managing Indoor Climate Risks in Museums

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# Foreword

Just before the end of the second millennium, the Ministry of Education, Culture and Science launched the so-called Deltaplan to save the cultural heritage in the Netherlands. Extra finances were provided to the heritage institutes to improve documentation and preservation. Conservation treatment was considered the next step. The impact of the Deltaplan was enormous on a national scale. New repositories and museum galleries were built, and existing housing was upgraded to the highest standards of collection preservation. All collection rooms were equipped with mechanical improvements to upgrade air conditioning and air purification.

In those days, our Cultural Heritage Agency (RCE) issued for the first time a publication on *Passive Conservation: Climate and Light* in which the specifications for the museum indoor climate were provided. The recommended climate specifications were formulated based on the maximum achievable safety for highly moisture-sensitive materials and applied to all types of collection assuming implicitly that all objects were of equal value. Due to the application of these rather strict specifications, many historic buildings redesigned as museum buildings have been rigorously adapted to the needs of the moveable collection.

In later years it became more and more apparent from published research and non-published experiences worldwide that relative humidity fluctuations do not always lead to a high risk of mechanical damage; collections are better preserved at lower temperatures; financial aspects of climate control are becoming more and more important; and technological innovations make it possible to allow for a more sustainable approach in climate control.

The dissemination of this knowledge is of particular interest to us, since it is the mission of our agency to help heritage managers in the Netherlands and abroad to get the best out of our heritage and preserve it for a long period of time. I believe that my colleagues Bart Ankersmit and Marc Stappers have succeeded to realize this ambition by the nine-step decision model to manage climate risks presented in this book. They have been able to develop this model that will allow practitioners to use science to better face their challenges. With this book, I hope and expect that the Cultural Heritage Agency, acting at the heart of heritage management in the Netherlands, reaches out to many at home and abroad to manage their climate risks optimally so that generations after us can enjoy our heritage as we can today.

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# Acknowledgements

This publication is a translation and expansion of the original Dutch Climate guidelines *Klimaatwerk* published in 2009. This text was translated into English by Luiz Pedersoli with the financial support of the program ‘Shared Heritage’ of the Cultural Heritage Agency. The information was used in teaching several international workshops titled ‘Managing Indoor Climate Risks’. In these workshops, we were able to use the feedback from both users of *Klimaatwerk* and the participants of our workshops to develop a more practical approach to the decision making process.

We decided to add extra steps to cover human comfort, building needs and background information about building physics into the decision making process. In addition, the contents of the other steps were updated. We would like to express our appreciation and thanks to Lisje Schellen, Rick Kramer, Roman Kozlowski, Morten Rhyl Svendsen, Tom Strang, Marion Mecklenbrug and Shin Maekawa and many others for their help by reading drafts of (parts of) chapters, suggesting improvements and providing references. We also would like to thank Naomi Luxford for editing the manuscript and making valuable suggestions for improvements.

The publication was made possible with the financial support of the ‘Sustainable Heritage’ program and ‘Shared Heritage’ program of the Cultural Heritage Agency. We hope that this work will contribute to a more sustainable optimization of indoor climates in heritage institutes all over the world.

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# Contents

# Chapter 1
# Introduction

**Abstract** In this chapter the history of climate control is presented. Discussing the climate in an unheated museum in the late nineteenth century, to the extremely dry environment in a heated building in the early twentieth century. Experience with collection preservation during the Second World War indicated the positive effect of a stable relative humidity. Since the mid twentieth century the set point for the relative humidity and temperature closely followed the technical development of climate systems. Resulting in an uncontrolled increase in energy demand. The effect of these adaptations on the building and climate control systems was enormous. Confidence in the technology grew, all though in practice numerous examples exist of malfunctioning of these systems. The overall risks to the moveable collections have increased to an almost unacceptable level.

With this publication collection managers and stakeholders are assisted; by providing information that will allow responsible decisions about the museum's indoor climate to be made. The focus is not only on the outcome, but also on the equally important process, which leads to that outcome. Nine consecutive steps are proposed to structure the decision making: valuation, assessment of the collection needs, the building needs, human comfort requirements, preparing for a balanced decision, understanding the building physics, climate control strategies and finally a cost-benefit analysis to make a choice.

**Keywords** History of climate control • Decision making process

## 1.1 Introduction

This publication elaborates on different aspects of the decision making process when managing climate risks in museums and historic houses. The Dutch climate guidelines 'Klimaatwerk' (Ankersmit 2009) form the basis of this publication. At that time it was recognized that a large knowledge gap existed in the Dutch heritage field regarding how the indoor climate reacted with objects of cultural value. Additionally that stakeholders involved in the decision making process for climate control in heritage institutions were often opposing instead of collaborating parties. Most often, this 'fighting' process did not lead to a consensus in which the chosen climate control strategy respected both the needs of the building and those of the

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moveable collection. Many examples exist, not only in the Netherlands, of historic buildings that have been rigorously adapted to the needs of the moveable collection without considering the building fabric. It became very clear in 2008 that the dissemination of background information, to assist decision making for the optimal management of indoor climate risks, was an essential task for the Netherlands Institute for Cultural Heritage (ICN), now Cultural Heritage Agency of the Netherlands (RCE). As the Dutch publication has been used for 5 years and the decision making process field-tested in several (inter)national workshops, it is now possible to update the publication.

## 1.2 A Short History of Climate Control

Objects of great cultural value have always been collected, used and shown to a broad audience. Early museums and the houses of collectors would have been relatively humid and often unheated.

The National Museum in central Stockholm (Sweden) was built in 1860 and unheated until 1862. Concerns about the low temperatures were raised and floor heating was installed. The system, with hot water, which was only used during opening hours, was able to raise indoor temperatures up to 16 °C (60.8 °F) above outdoor temperatures. In 1902 complaints were made because winter temperatures in the ground floor galleries were around 10 °C (50 °F), while the restorers' workshop, in the attic, temperatures were as low as 0–6 °C (32–42.8 °F). As fire risks were considered too high, no stoves were allowed in the attic. Due to the large temperature differences between day and night time, condensation was a major risk to both building and collection. Condensing water was collected and channeled into large tanks. In one single night as much as 1000 l of condensed water could be collected inside the building (Legnér 2011). When in 1923 a new heating system with electrical stoves was installed, the temperature on the first floor could be raised to 18.5 °C (65.3 °F) in April, while in that same room in December 1922 the temperature had been −0.8 °C (30.6 °F). As a result, the relative humidity dropped to levels never before experienced by the collection (see Fig. 1.1 in which the orange arrow shows a relative humidity drop to approximately 20 %) resulting in clearly visible shrinkage of all wooden objects in that room. This forced an immediate shutdown of all heating. From this trial it became clear that room temperatures could be increased to human comfort levels, which encouraged the museum to satisfy the increasing numbers of visitors to the museum. A forced air ventilation system without humidification was installed in 1931 as the risk of mechanical damage was expected to be very low (the damage observed 10 years earlier was clearly forgotten). Unfortunately the Dutch collection of panel paintings cracked during the first winter and humidification needed to be added to the control system, which was implemented in 1932 (Legnér 2011).

One of the first museums to have a rudimental air conditioning system installed was the Boston Museum of Fine Arts in 1908. The air that fed into the exhibition

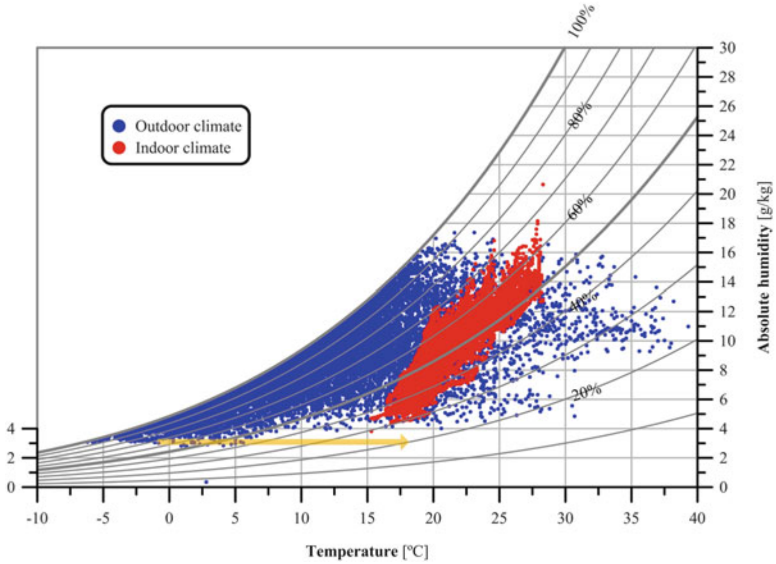

**Fig. 1.1** Relative humidity, temperature, and calculated specific humidity outdoors (*blue data points*) between 2001 and 2005 in the Netherlands, and inside a heated historic interior without influencing the moisture balance over the period of January 2005–January 2006 (*red data points*) (Source: outdoor climate data from the Dutch National Institute for Public Health and the Environment – RIVM website, and indoor climate data registered every 30 min by The Cultural Heritage Agency). The *orange arrow* shows the resulting relative humidity drop due to heating in the National Museum Sweden from −0.8 to 18.5 °C (30.6–65.3 °F)

rooms was passed through a washer and humidifier, this way the relative humidity was maintained at 55–60 %. In the Cleveland Museum of Art dehumidification was considered, but found to be too expensive for the expected limited use during the two summer months per year (McCabe 2013). In 1934 a more elaborate system of 1740 lb of buffering canvas, spray humidifier and heater, with fans was supposed to maintain the relative humidity in the conservatory of Hampton Court Palace between 55 and 75 %, even though summer temperatures could be as high as 27 °C (80 °F) (MacIntyre 2013).

In 1935 the Gemeentemuseum in The Hague was opened. Berlage paid much attention, in his design to the technical equipment of the building, such as the natural and artificial lighting of the rooms. Since central heating was believed to be “an enemy of museums”, three different heating methods were installed (Luciani 2013). Panel heating was chosen for the galleries of paintings. The system was based on warming structure surfaces with a large piping network circulating water at lower temperature than radiators and thus originating a comfortable direct uniform heat radiation. Radiating panels were placed on the ceilings, into the floors and into the walls, even if this was not a usual application at the time.

Steam radiators were installed in service and staff rooms, in the library, in the cabinets and in the rooms where ancient furniture and wooden objects were exhibited. Radiators were turned off during the night: "this interruption allows to obtain the cooling that is fundamental to prevent the drying of the woodworks". Humidifiers were in use in all the heated rooms and RH levels were measured by hygrometers to prevent damage. Finally in the conference room and in the entrance hall an air system was installed.

At the same period, the National Gallery in London employed a technician for some 8 months per year to deal with climatic damage such as cracking, blistering and flaking (Keeley and Rawlins 2013). When the Second World War broke out, plans were made to protect the collections in London from bombing and the additional risk of fire by relocating the collections to safer places. The collections of the V&A, British Museum, the National Portrait Gallery and about 30 other institutes were relocated in a quarry at Westwood, some 90 ft below ground. The walls were covered with a waterproof barrier and an air conditioning system to maintain the temperature between 15.6 °C (60 °F) and 24 °C (75 °F) and the relative humidity between 60 % and 65 %.

The 2000 paintings from the National Gallery were stored in the *Manod* quarry in Wales. The storage buildings were heated to 17 °C (63 °F) resulting in a stable relative humidity of 58 % for the rest of the war (Davies and Rawlins 2013). These stable conditions, proved very favorable to the sensitive collections. Upon their return to the museum an epidemic of blisters, cracks, and deformations broke out on the paintings as a result of poor climate conditions inside the museum building (Keeley and Rawlins 2013). Before the war, the scientific laboratory at the National Gallery had already investigated the moisture content of different species of wood in the exhibition gallery across the seasons. This determined that the yearly average equilibrium moisture content was 11 %, which corresponds to a relative humidity of 55–60 % (Keeley and Rawlins 2013).

It seems that by the 1940s climate control installations were more or less universally considered a required feature for museum collections. Air conditioning systems represented the state of the art and the favorable solution to engineers and conservators but still they involved problems which limited their spread, in particular high costs. The awareness that mechanical damage could be reduced by stable environmental conditions coincided with the technical developments of climate control systems. From the 1950s, systems became available which could influence the moisture balance in buildings, and disconnect to some extent, the indoor climate from the outdoor conditions (Brown and Rose 1996; Erhardt et al. 2007; Legnér 2011). Plenderleith rationalized the lowest acceptable and highest acceptable limit of relative humidity for museum galleries. He stated that, based on the 'seasoning' of wood, 50 % is the minimum value below which organic materials will be damaged by desiccation and 68 % is the absolute danger limit for mould at temperatures between 15.5 °C (60 °F) and 24 °C (75 °F) (Plenderleith and Werner 2013).

Central heating was introduced in the beginning of the twentieth century, but it only became commercially available for a wider public, including museums, from the 1950s. As a result uniformly heated spaces could be efficiently created. However, there was a downside effect during the heating season: the relative humidity

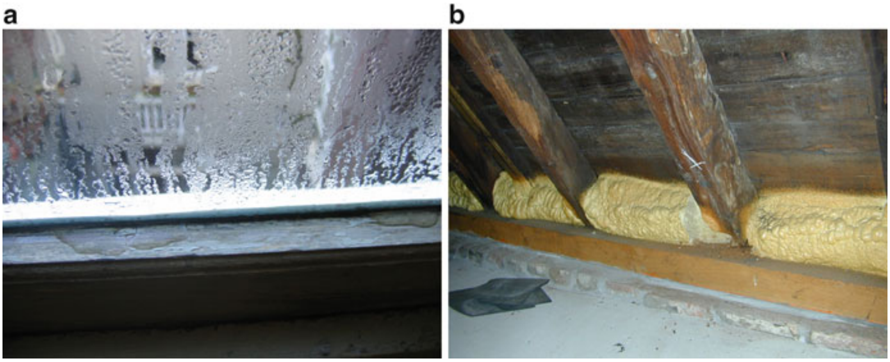

**Fig. 1.2** Rotting of wooden window frames has been accelerated by condensation on single glass panes (**a**). Despite insulation, the wooden beam heads rot faster due to a combination of locally lower temperature and a subsequent locally increased relative humidity (**b**) (Photo: Hermans, Cultural Heritage Agency of the Netherlands)

decreased significantly, to much lower levels than museum collections were previously exposed (Maekawa et al. 2007). In order to reduce the risk of mechanical damage due to excessively low relative humidity, the air had to be moistened. Many museum collections, however, were housed in buildings that were not designed and built for this type of humidity and thermal control. Changing the humidity and temperature in these buildings required a number of structural adjustments. Therefore, reducing climate risks to the collection in this way often implied increasing the climate risks to the building. Humidified air condensed on cold surfaces in the building envelope that had previously remained dry, and wooden parts rotted at an accelerated pace (Fig. 1.2). So, the collection could be better preserved, but at the expense of the condition of the building fabric.

In the first edition of the well-known, extensively quoted but less critically read, publication *The Museum Environment* by Garry Thomson (1978), a relative humidity set point of 55 % with an acceptable fluctuation of plus or minus 5 % is proposed. The author adds, nevertheless, that:

> *We have a very uneven knowledge of how fast things in the museum change and what causes these changes, and yet we have to erect this framework of preventive conservation before rather than after our research has reached a dignified level of completion.* [. . .] *But the question of how constant relative humidity needs to be to ensure that no physical deterioration will occur at present remains unanswered. The standard specification of ±4 or ±5 % in relative humidity control is based more on what we can reasonably expect the equipment to do than on any deep knowledge of the effect of small variations on the exhibit.*

The value of 55 % was probably chosen as a London average. In 1986, Thomson published a second, updated edition of *The Museum Environment*. Two indoor climate classes were proposed: Class 1, with strict control (50 ± 5 %) or (55 ± 5 %) using HVAC systems for all national museums and all important new museum buildings and Class 2 (40 % < RH <70 %) using mobile (de)humidifiers (Thomson 1986).

The development of climate control can be briefly summarized. Starting with no heating or just some basic heating of the exhibition rooms, with low human comfort levels during cold seasons. After which the heating is optimized to reduce discomfort so that even at low outdoor temperatures, indoor temperatures of 18–22 °C (64–72 °F) can be reached. These relatively high indoor temperatures cause damage to hygroscopic artifacts and require an optimization of the humidification, keeping the relative humidity roughly at 40–60 %. In the last decades of the twentieth century a optimization of (de)humidification by HVAC systems with larger capacities (i.e. strict climate control) took place. The effect of these alterations on the indoor climate is nicely shown by a hygrothermal building simulation of the Alte Pinakothek over its long history (Eibl and Burmester 2013). A comparison of the six climatic phases of the building showed that 'since the 1950s, the set point for the relative humidity and temperature have closely followed technical equipment improvements'. Resulting in an uncontrolled increase in energy demand. The effect of these adaptations on the building and climate control systems is illustrated by photos of the Rijksmuseum, Amsterdam presented in Fig. 1.3.

At the Smithsonian Museum Conservation Institute (formerly known as the Conservation Analytical Laboratory) research undertaken in the 1990s focused on the dimensional response of individual materials found in cultural objects, arising

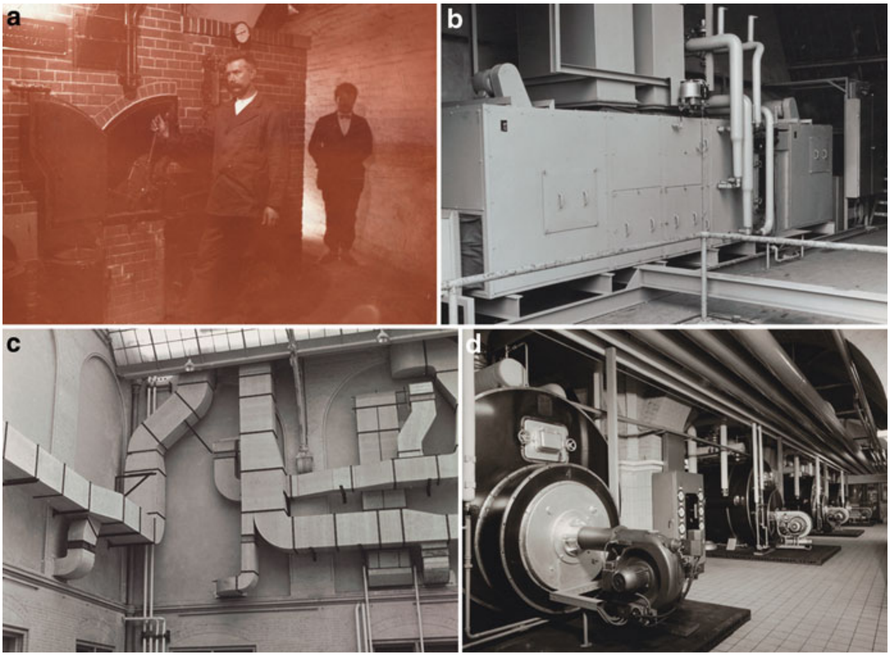

**Fig. 1.3** The Rijksmuseum, Amsterdam climate control development through the twentieth century: (**a**) the coal oven in 1920, (**b**) the climate system in 1960, with (**c**) duct systems in the court yards in 1959 and (**d**) the new climate systems in the 1970 (Photos provided by the Rijksmuseum Amsterdam)

from environmental changes. The development of stresses and strains for materials such as animal glues, gesso, different species of wood and oil paint induced by relative humidity fluctuations were measured and calculated. Based on these experiments the allowable relative humidity fluctuations that produced only reversible changes in collections were presented. The risk of fracture depends strongly on the annual average around which these fluctuations occur. For an annual average relative humidity set point of 50 % there is a smaller risk of fracture due to fluctuations of a certain amplitude, than that resulting from similar sized fluctuations around a set point of 30 % or 70 % (Mecklenburg et al. 1994; Kozłowski 2007). This means that a relative humidity of 50 ± 10 % represents a much smaller risk of permanent deformation or fracture than an indoor climate with a relative humidity of 65 ± 10 %, despite the fact that the fluctuation is the same in both cases.

In 1994 a press statement was released by the Smithsonian in which the new climate guidelines were presented. Moderate fluctuations within the range of 50 ± 15 % were considered safe. Current guidelines at the Smithsonian state a relative humidity of 45 ± 8 % and a temperature of 21 ± 2 °C (70 ± 4 °F) (Erhardt et al. 2007).

Specifications for the museum indoor climate were also established in the Netherlands, partly in response to Thomson's *The Museum Environment* publication. In 1994, RCE's predecessor, the Central Research Laboratory, issued a publication on *Passive Conservation*: *Climate and Light* (Jütte 1994). The recommended climate specifications were formulated based on the maximum achievable safety for highly moisture sensitive materials, and applied to all types of collection. Moreover, the requirements became increasingly strict over the years. In 1994 it was generally recommended that the relative humidity should be kept between 48 % and 53 %. The general thought was that if ±5 % is good, ±3 % is better. Ten years later this line of thought resulted in a required relative humidity bandwidth of ±1.5 % around a set point of 51 % and a temperature of 18 ± 1.5 °C (64 ± 2.7 °F) as stated in the technical specifications for a medium-sized city museum housed in a medieval leaky building (Ankersmit and Stappers 2011).

In 1999 the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) published for the first time in its Handbook, a chapter dedicated to design guidelines for the indoor climate in museums, libraries, and archives. In that publication, relative humidity and temperature levels are not approached in terms of the different classes of materials, but rather by the corresponding risks of damage. This risk-based approach is also the starting point for the present guidelines, with some adjustments. Differing from chapter 21 of the ASHRAE Handbook, the decision making process described here is placed in the 'bigger picture' context of the building and the (movable) collections, taking into account the values attributed to both.

The 50 % relative humidity set point selected by many museums in northern Europe and North America is not chosen completely arbitrarily. This value is close to the average relative humidity of a heated room in northern Europe. For example in Fig. 1.1, the indoor climate of a heated historic room shows an average temperature of 20.8 °C (69.4 °F) and a relative humidity of 49.5 %. Another reason for selecting a 50 % set point is that climate extremes represent a significantly higher risk of mechanical damage to museum collections.

The ambition to reduce relative humidity fluctuations to a minimum meant that many museums made (unnecessary) great efforts to try and meet those extremely stringent indoor climate targets, including for spaces in which materials with low moisture sensitivity were kept. Moreover, to meet the climate specifications required large climate equipment with wide ducts. In buildings the design, installation, and control systems of these functions are integrated into one or more HVAC systems. Implementation of such systems involves extensive interventions in the building, and loss of space due to the increasingly large components. The operating costs have also become increasingly high as stricter target conditions for the indoor climate were defined.

Confidence in the technology grew so much that some museums did, and still do not, perform their own, independent of the installation, control measurements near the objects to check if climate specifications are met. Meanwhile, many people have seen, in their own practice, climate control installations that kept humidifying the indoor environment as a result of malfunctioning sensors, resulting in a widespread mold outbreak. These professionals are also familiar with the lack of a warning system to indicate that threshold values have been exceeded on warm days due to a failure of the cooling system. On the other hand, there are installations that give false alarms so often that their alarm function is switched off out of despair. We know of situations in which only a few sensors placed in a room or zone are used to drive the climate control installations, based on average readings. There are also installations that operate in response to non-calibrated sensors located inside the air ducts of the installation itself. As already outlined, the invisible, climate can be a large threat to collections and therefore should be made visible, by measuring continuously and independently from the building systems.

More and more became apparent from research and non-published experiences that relative humidity fluctuations do not always lead to a high risk of mechanical damage; collections are better preserved by lower temperatures; financial aspects of climate control are becoming more and more important and technology can allow a more sustainable approach to climate control. With this publication we hope to present to the reader the results of research carried out since the 1980s, which has provided a new insight into the magnitude of risk of damage resulting from an incorrect indoor climate. This approach requires an understanding of the values of all the heritage items involved; building and collection. Weighing the collection values (i.e. significance) with those of the building is a first step in identifying possible climate control strategies. A transparent way to manage indoor climate risks, taking into account both building and collection, is presented in nine steps. The text ends with conclusions and recommendations. The annexes include a list of consulted literature, a glossary of terms mentioned in the text, a general overview of risks that can threaten collections, and the mathematical equations used for lifetime calculations, and to convert relative humidity into absolute humidity.

In practice, climate control measures are often coupled to other measures to minimize the effects of theft, fire, light, and poor air quality. For more information about light the reader is referred to the publication by the International Commission on Illumination (2004). Apart from the indoor climate, Chapter 23 of the ASHRAE Handbook (2011) also deals with the most relevant aspects of air pollution. For additional information the reader is referred to Tétreault (2003).

## 1.3 Nine Steps

The goal of this publication is to assist collection managers and stakeholders by providing a decision making model, with background information that will help responsible decisions about the museum's indoor climate to be made. The focus is not only on the outcome, but also on the equally important process that leads to that outcome, see Fig. 1.4. The nine steps help in structuring a complex decision making, in which complex information on a molecular scale needs to be weighed and combined with complex information on a macro scale of controlling the indoor climate on a building level.

Working within a framework and documenting the process, as developed in for example the freely available collections management standard SPECTRUM (Collections Trust 2011), also promotes transparent decision making and facilitates information exchange and consultation among stakeholders. Here lies a big challenge, since in practice it is not easy to bring together all the expertise and use this knowledge to develop an optimal solution, despite the availability of a systematic decision making methods. In auditing three former national museums carried out by the Dutch Cultural Heritage Inspectorate it was shown that, the prevailing indoor climate was far from the desired conditions. The underlying documentation, such as the climate specifications in the program of demands, that should serve as a basis for decision making and record the choice of measures, was not available (Erfgoedinspectie 2007). Documenting the process and the decisions made, including the corresponding arguments, is essential to ensure that the next generations will have a clear understanding of today's choices.

The decision making process that helps choosing a climate strategy that best fits the institutional ambitions, the collection and the building needs includes nine steps:

Step 1 In Step 1: **Towards a Balanced Decision** the decision context and decision process is explored. The individual goals of the heritage institute and the stakeholders involved are expressed and attributes assigned. The aim of expressing the goals and attributes explicitly is to be able to analyze the success or failure of the outcome.

Step 2 In Step 2: **Valuing Heritage Assets** the significance of the building and the movable collection are made explicit. Altogether, the values and significance provide the framework within which options for modifying the building and/or the environment around the objects can be considered

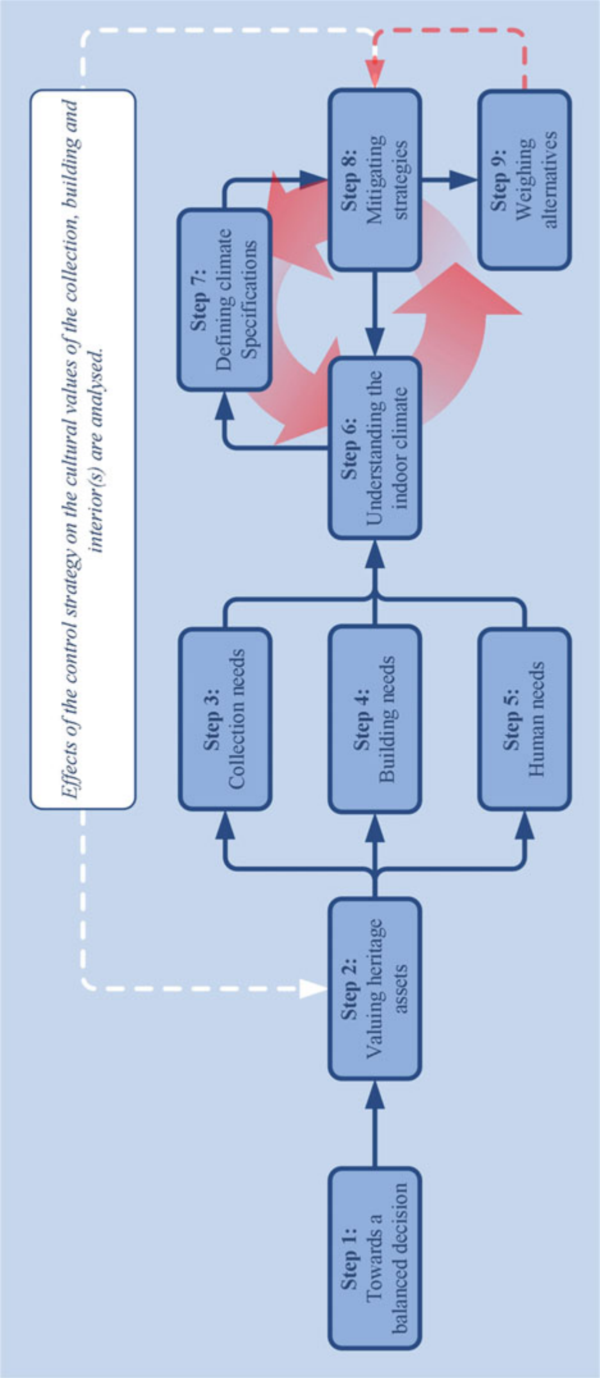

**Fig. 1.4** A schematic representation of the nine step process to manage indoor climate risks

and evaluated. The overall aim of the decision would be to give as much cultural value to future generations as possible.

Step 3 In Step 3: **Assessing the Climate Risks to the Moveable Collection** the collection needs are defined. The collection can be divided into sensitivity categories containing materials/construction/objects that have different environmental needs. Subsequently, the climate-related risks that must be reduced are determined for each category.

Step 4 In Step 4: **Assessing Building Needs** those parts of the building that are considered valuable and susceptible to certain climate conditions are identified. The building materials can be divided into sensitivity categories containing materials/objects that have different environmental needs. Subsequently, the climate-related risks that must be reduced are determined for each category.

Step 5 In Step 5: **Assessing Human Comfort Needs** the climatic requirements for the human occupants are defined for each climate zone.

Step 6 A building provides an (natural) environment with a certain indoor climate. Step 6: **Understanding the Indoor Climate** allows an assessment of the building envelope properties that can be optimized to reduce risks to the moveable and immoveable collection.

Step 7 The climate needs for collection, building and humans are combined with the understanding of the indoor climate and the objectives to develop the climate specifications for the climate zones within the building in Step 7: **Defining Climate Specifications**.

Step 8 In Step 8: **Mitigating Strategies** a strategy for the efficient and sustainable implementation of climate control is then developed. Within the value framework established in Step 2, the options to improve the indoor climate are considered and selected.

Step 9 In Step 9: **Weighing Alternatives** a cost-benefit analysis is undertaken. Alternative options to reduce the climate collection risks are evaluated by the amount of risk reduced, cultural values lost and financial investments to be made.

Application of these nine steps will not always be easy for every collection manager. Detailed information needs to be gathered, digested and analyzed and this takes time and effort. Yet the assessment of different possible options to reduce climate related risks to the collection, or building, to an acceptable level is primarily the responsibility of the collection manager. In some cases (s)he will be able to decrease the time spent, by choosing the most appropriate decision making path:

- Whether or not to use a valuation framework
- To divide the collection into sensitivity categories or assume a mixed, highly sensitive collection
- To look for solutions at the room, building or locally at the object level

The framework, within which decisions are made, however, will have narrower limits if it involves changes to protected historic buildings for which a special permit is required. In these cases the value of the monument or the ensemble primarily determines what can and cannot be done.

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# Chapter 2
# Step 1: Towards a Balanced Decision

**Abstract** The starting point for any decision to be made, including optimizing an indoor climate, is knowing what the context of the decision is. Which problem am I solving? Which (part of the) collection is at risk? What will happen to the building if control strategies are implemented? Who needs to be involved? How much money will it cost?

When it is decided to optimize the indoor climate the first step is to identify what is important to the different stakeholders for the decision at hand. The process starts by specifying the most important values and by developing a list of anything that collection managers or stakeholders care about, with regards to the possible consequences that may result from the decision to be made. The decision making can be improved by translating general ambitions into a set of objectives. These objectives are ideally provided by stakeholders.

To measure the success of any decision outcome, some kind of measure or unit for each objective is defined. These are called attributes. The use of attributes allows a quantified analysis of the success of a (preservation) decision. To structure the decision making process to manage indoor climate risks, nine separate steps are introduced.

The decision making that took place during a project in which a seventeenth century Dutch historic house was made suitable for a museum function is discussed.

**Keywords** Decision context • Mission statement • Objectives • Stakeholders • Attributes

## 2.1 Introduction

Optimal decision making starts with the identification of which issue is being addressed and why it is important. Gaining a clear and common understanding of the question, or challenges, is often harder than it seems, but is key to working on the answer. Roles and responsibilities should be clearly established, including identification of the ultimate decision maker. Stakeholders and key technical experts are identified, and their role in the decision process defined. It is also important to identify the constraints within which the decision will be made. These might include, legal and/or financial constraints. One of the most important

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characteristics of a decision is the context in which it takes place. Context includes the set of values, preferences, constraints, policies and regulations that will affect both the decision makers and those identified as the ultimate beneficiaries. Managing indoor climate risks often involves national standards, loan requirements, or regulations related to the building. It should be noted that this context is not static, it is time dependent. Decision-makers therefore need not only to understand the environment in which the decision is made today, but also the one that will be when the options are implemented and the effects of that are clear. This analysis involves activities such as consulting with stakeholders, researching legislation, assessing attitudes, analysing issues, understanding priorities, identifying obligations and reviewing national policies.

In this publication we work towards affordable, tailor-made, indoor climate conditions for collections and the building based on: the value of the building and the collection (Chap. 3: Step 2); the climate risks to the collection in the present situation (Chap. 4: Step 3); the climate risks to the building (Chap. 5: Step 4); and human comfort requirements (Chap. 6: Step 5). Bringing these arguments into the decision making process and weighing these findings against other ambitions, requirements and boundary conditions is a complex process. In real life the climate specifications depend not only on the cultural values, the susceptibility of the building and the collection, and the comfort requirements, but also on other arguments such as financial and technical feasibility, and the desire to have incoming loans, which can often play a much more important role in the final climate specifications. Based on the publication 'Value Focussed Thinking' by Keeney (1992), this chapter provides a structure to help specify the indoor climate.

Once the need for managing the indoor climate risks; or the ambition to generally improve the indoor climate; or to renovate the building and its systems; or even to build a new (storage) building is identified, the next step is to develop a framework to help guide the decision(s) to be made.

## 2.2 Starting with What's Important

The first step is to identify what is important to the collection manager and stakeholders for the decision at hand. The process can start by specifying the most important values and to create a list of anything that the collection manager and stakeholders care about, with regards to the possible consequences that may result from the decision to be made. A good way to identify these general values is to interview stakeholders and ask "What would you like to achieve?" or "What would you hope to achieve if there were no limitations?" Sometimes it can be helpful for developing new values, to think about alternative approaches to optimize the indoor climate and to analyze their potential consequences.

As an example, a conservator of a historic house museum would like to improve the relative humidity during the cold winter season. Obviously an important value to the conservator would be preservation of the collection. In thinking about ways to achieve an optimal preservation by humidification, the options of mobile humidification and the application of microclimate boxes come to mind. Mobile humidification would result in placing a relatively large machine in the historic interior, while the use of microclimate boxes involves a glass barrier between visitor and object. Both measures seem to be big issues. The mobile humidifier would affect the experience and aesthetics of the historic interior, while the glass barrier would reduce the 'contact' between artwork and visitor. So two new values for decision making are developed: *historic appearance* of the room and *access to the object.*

Ideally the process allows everyone involved to bring their own criteria, values and objectives. In an iterative process the options are developed by a group, which results in a list of values, which possibly generates ideas about new options, that again might produce new values.

### 2.2.1 Using the Mission Statement as a General Basis to Develop Values

Decisions made for any company are based on several ambitions, the most generic ones are provided by the mission statement. The most common objective probably is to generate income or reduce expenditure. But other aims, could include having a certain image, being environmentally friendly, caring for (a specific group in) society, etc.

A mission statement is a text that clarifies the purpose or higher ambitions of an (heritage) organization, it explains the reasons for existing. The mission statement should guide the actions and support decision making in the organization. It provides the context within which the company's strategies, including the preventive ones, are developed.

As an example a general art museum mission statement was developed based on several mission statements of 15 internationally operating museums throughout the world.

> The mission of the museum is to collect, preserve, study, exhibit, and stimulate appreciation for and advance knowledge of works of art to as many people as possible, now and in the future, in order to enrich and inspire them.

The general values that can be distilled from this mission statement are that the museum has collection growth and wants to give access to the collection (for study and enjoyment).

Even though the mission statement provides the general aims of the heritage institute, it is hardly ever used in practice to explicitly guide decision making when the indoor climate is optimized. Generally, despite the mission statement including the ambition to preserve, often other people, with other arguments, overrule the decision making.

### 2.2.2 Involving Stakeholders

Decisions about managing indoor climate risks are hardly ever made by one person. When more people, i.e. stakeholders, are involved, more opinions and ambitions will influence the final decision and its outcome. It is important to frame the decision and develop options with the optimum number of stakeholders, as well as those stakeholders that really have an impact on the decision to be made. Finding the right person, with the right knowledge and with the right level of influence, will vary. Generally in larger projects representatives of the museum, such as the director/facility manager/conservator/curator, an external (conservation/restoration) architect, building physics and or climate systems engineers, conservation and or building physics scientists and often civil servants as project manager or historians are involved. It is essential that the stakeholder group discusses the different ambitions, the things they individually feel are important and tries to reach consensus about the most important values in the decision to be made.

Transparency and consensus is important because generally there are shared interests, but unfortunately often with conflicting outcomes. Museums attract people by providing a welcoming environment, with space and light. Attractive architectural designs that sometimes are art in themselves, but not necessarily improving the building physics, have become more and more important to accentuate the collection and improve the visitor experience. The Guggenheim museum in Bilbao, designed by Frank Gehry and opened in 1997, with its titanium plates and steel columns lacks a high amount of thermal mass that could provide some thermal buffering against the Spanish climate. Many museums that were refurbished in the past decades built extensions, in which control of the indoor climate is either very expensive, or almost impossible to achieve, without accepting fluctuations and/or gradients. *The Crystal* designed by Daniel Libeskind for the Royal Ontario Museum and opened in 2007, proved to be quite a challenge for the staff responsible for collection preservation (Coxon 2007).

Energy consumption and the related costs, has become more and more of an issue for museums. After a period in which full climate control of museums was common practice, nowadays sustainability and smaller budgets urge museums to look for alternatives without compromising their preservation ambitions. Museums are investigating ways to reduce the energy demand, by optimizing the climate control strategy and/or improving the building physics, or using sustainable energy sources, such as solar radiation and heat pumps. To measure the results, or the sustainability ambition, energy consumption per square meter of floor space (KWh/$m^2$) could be used.

## 2.3 What Do We Really Want?

If we know what we want, we should aim to be as transparent and as clear as possible. We can try to improve our decision making by translating general ambitions into a set of objectives. These objectives are provided by stakeholders that are knowledgeable about the decision. There are different ways and devices that can help to stimulate the identification of possible objectives (Keeney 1992).

Every objective has three features: (1) the context of the decision, (2) it has an object and (3) it has a direction of preference. An example of an objective for a museum that considers improving their website could be to "maximize the number of visitors", the object is number of visitors and the direction is more, rather than less, visitors. The decision context here is investing in a website.

In developing objectives two questions can be asked: 'Why is *it* important?' and 'What do you mean by *it*?' A museum example would be the improvement of the indoor temperature during hot days by air conditioning. This is important, because visitors complain and even faint sometimes, if it gets too hot. So visitor comfort during hot summer days should be improved, but how often and to what temperature? So a following question would be, at what indoor temperature do visitors start to complain, during which part of the day and how often per year are these indoor temperatures reached? A possible objective would be 'maintaining indoor temperatures below 26 °C (79 °F)'.

As an example of developing objectives, the mission statement can be used. This helps in designing a rough outline for the strategy to achieve these ambitions. Using the general museum statement given above, the ambitions or objectives of this hypothetical heritage organization can be made very explicit. Focusing on the preservation ambitions and the strategies, which are subsequently developed to reach those ambitions, the generic terms related to preservation could be clarified and described in more detail.

*Collect works of art* involves maximizing the overall collection value by accessioning of a non-specified number of new (susceptible) objects that require additional storage or exhibition space.

*Preserve works of art*, states the ambition to minimize the rate of deterioration of the total collection and building.

*Study works of art* describes the wish to maximize access to (the cultural values of) the collection by students and researchers.

*Exhibit works of art* is using all or part of the collection to maximize access to (most of the cultural values of) the collection to the general public.

*Stimulate appreciation for works of art* requires an 'intimate contact' between visitor and the (cultural values of the) objects and can be described as maximizing access to the collection value.

*Advance knowledge of works of art* describes the ambition to maximize access to knowledge and information about the object(s) and it's (their) cultural context.

*To as many people as possible now* clarifies the ambition to welcome everybody today and in the near future.

*To as many people as possible in the future* is closely related to the preservation ambition, to present the (cultural values of the) objects to some point in the (far or very far?) future and thus to minimize the rate of deterioration of the total collection.

There are a (great) variety of objectives that can be generated by the different stakeholders in large decision making contexts. The conservator will be focused on damage to collections (loss of cultural value), the scientist will have the ambition to use the newest information and techniques, the project manager is aiming to deliver the project on time and the exhibition designer wants the exhibitions to look great. From these examples it becomes clear that not only do the objectives differ, but also the nature of the objectives. Some objectives are related to the process or to a general institutional ambition rather than to a fundamental aim.

Four different types of objectives can be distinguished. There are objectives related to the way, i.e. the process, the decision is made and not so much to the decision itself. These are called *Process objectives*. Examples of process objectives are the use of proper information to inform yourself about the decision, to communicate with all stakeholders, or to publish the final decision outcome. Another type of objective is related to the responsibility of the organization, called *organizational objectives*. An example related to managing indoor climate risks could be to ensure public acceptance or to contribute to the credibility of the museum. The third type of objective, called a *means objective*, looks like a fundamental objective, but is not really fundamental. An example would be the objective to reduce the relative humidity in summer, while the *fundamental objective* would be to reduce the risk of mechanical damage. The latter is also called the ends objective. It describes the consequences that essentially define the basic reasons for being interested in the decision (Keeney 2004). The challenge is to identify the most relevant objectives for the decision, structure these and focus on the fundamental ones.

## 2.4 Making Objectives Measurable

To measure the success of any decision outcome, here a climate strategy, requires some kind of measure or unit for each objective; these are called attributes. The use of attributes allows a quantified analysis of the success of a (preservation) decision: are the ambitions really achieved? Using attributes also allows a more transparent decision making process. The attributes should be chosen so that they fit the decision to be made. If the objective is to maximize preservation of oil paintings on panel, an attribute could be the movement of the wooden structure. But one could argue that movement of the wooden structure does not always lead to damage and therefore to a reduction of preservation. In this case one has to clarify what does preservation of panel paintings mean exactly: Maintaining the current number of cracks in the oil paint? Maintaining the current amount of paint loss? Or, maintaining the current crack length? By analyzing and making the meaning of a general objective explicit, one can start thinking about how to express the objective

**Table 2.1** Some objectives with possible attributes

| Objectives | Possible attributes |
|---|---|
| Minimize the rate of deterioration | Length of cracks (mm) |
| | Number of cracks (#) |
| | Surface area of mold ($cm^2$) |
| | Number of mold out breaks (#) |
| | Degree of polymerization (cellulose based materials) (#) |
| | Folding number (#) |
| | Tear and tensile strength (kN/m) |
| | Corroded area ($cm^2$) |
| | Color change: $\Delta E$ (−) |
| Maximize access to (the cultural values of) the collection | Number of visitors (#) |
| | Number of visitors to the study collection, e.g. reading room (#) |
| | Number of objects on (inter)national loan (#) |
| | Number of loan requests (#) |
| | Number of exhibitions (#) |
| Maximize income | €, £, $ |
| Minimize costs | €, £, $ |

and thus how to measure it. In Table 2.1 potential attributes for some generic objectives are listed.

The criteria are organized by clustering them under high-level and lower-level objectives in a hierarchy.

## 2.5 A Case Study

The real estate department of the city of Utrecht (Netherlands), was commissioned to examine the options to make the seventeenth century historic house Old Amelisweerd suitable for a museum function, see Fig. 2.1. Between 1950 and 2012 the house was uninhabited and managed by the Central Museum in Utrecht, the house could only be visited on appointment. The expected number of visitors for the new museum is 40,000–50,000.

The integral monumental value of the estate Old Amelisweerd can be characterized by its exceptional integrity, uniqueness and high cultural and historic value. This applies to the estate as a whole and in particular to the manor house, the coach house and park: all are largely unchanged since the seventeenth century.

The manor house has several unique interior values. Initially attention focused on the two outstanding Chinese wallpaper and painted linen hangings, but the layout of the house apartments, the indoor toilets, unique manually operated elevator are equally important. There is no other seventeenth century country estate in the Netherlands that allows a similar experience of the interior values. The integrity of this building is unique, even from an international perspective.

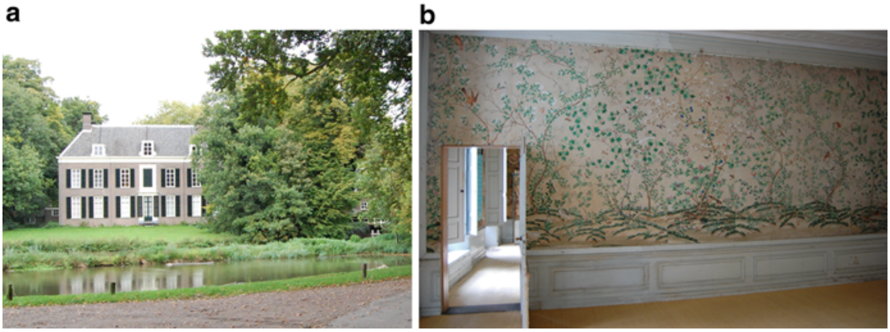

**Fig. 2.1** Old Amelisweerd, the Netherlands (**a**) with the wallpaper of high cultural value (**b**)

The project team consisted of an external project manager, civil servants from the city council (cultural historian and a real estate advisor), the Cultural Heritage Agency of the Netherlands, wallpaper conservator, climate engineer, the director of the new museum and the curator of the Central Museum. Each of the team members had an ambition with regards to developing the historic house as a museum:

- The representative for culture in the city of Utrecht stated that: "they'd prefer to use all the cultural value in the next 50 years by providing open access now, than have a 100 years of preservation without access". So the aim of the city council was maximizing access to the house with minimum costs and thus accepting (some) risks to the wallpaper.
- Central Museum aimed at sustainable access to cultural values for prolonged time, thus aiming at a mix of preservation and access.
- The Cultural Heritage Agency of the Netherlands indicated that "The house deserves a sustainable and appropriate future function and major structural changes should be avoided. Visitors are welcome, but there is a maximum number that can be accommodated. The uniqueness, historic and cultural values of the complex are too large. Aiming at a mix of preservation and access."
- Two external historic consultants indicated that the house was too valuable for any change and access should be minimized.
- The museum director wanted to show the modern art collection but with respect to the historic interior finishes, with a subtle balance of preservation and access to the general public.

The first discussions can be summarized by: the house should be opened to the public with access to everybody, but the current indoor climate is not optimal for the preservation of the wallpaper when many visitors come; temperature and relative humidity control becomes essential; insulation and double glazing is required to prevent heat loss and condensation problems in winter time; what is to be done with the wet coats of visitors?; a new entrance with wardrobe could solve this issue; but incorporating a reception area in the house would involve a large loss of historic and architectural value to the building; an underground passage between manor and coach house could prevent visitors becoming wet; the costs would be very high; the need for an under passage can be overcome by restricted access, visitor numbers will be lower so a limited climate control is needed.

The house has no central heating. Almost the entire interior is in prime condition and dating from the period of construction. Given the cultural and historical importance of the wallpaper in different rooms on the first floor, the climate in these rooms should be based on collection needs. Preservation of the wallpapers requires low temperatures, a more or less stable relative humidity and preferably a relative humidity somewhat lower than 50 %. This means that in the rooms with important wallpapers the indoor climate is preferably not, or only slightly heated and maybe slightly dehumidified. A low capacity climate system with heating, cooling and dehumidification function was placed in the attic (see Fig. 2.2). In the rooms without any susceptible and valuable wall finishes, i.e. the attic, the climate can be directed at human comfort needs. In the attic a visitors' center is created, which requires complete control of temperature for human comfort.

The walls with the Chinese wallpapers were not insulated. The minimum indoor temperature is maintained at 5 °C (41 °F) and a relative humidity around 55 %. Since the historic building is quite leaky which will ensure sufficient fresh air for visitors, it was decided to fully recirculate the indoor air.

**Fig. 2.2** A schematic presentation of Old Amelisweerd, showing the HVAC system in the attic, with the air ducts (located in historic air shafts)

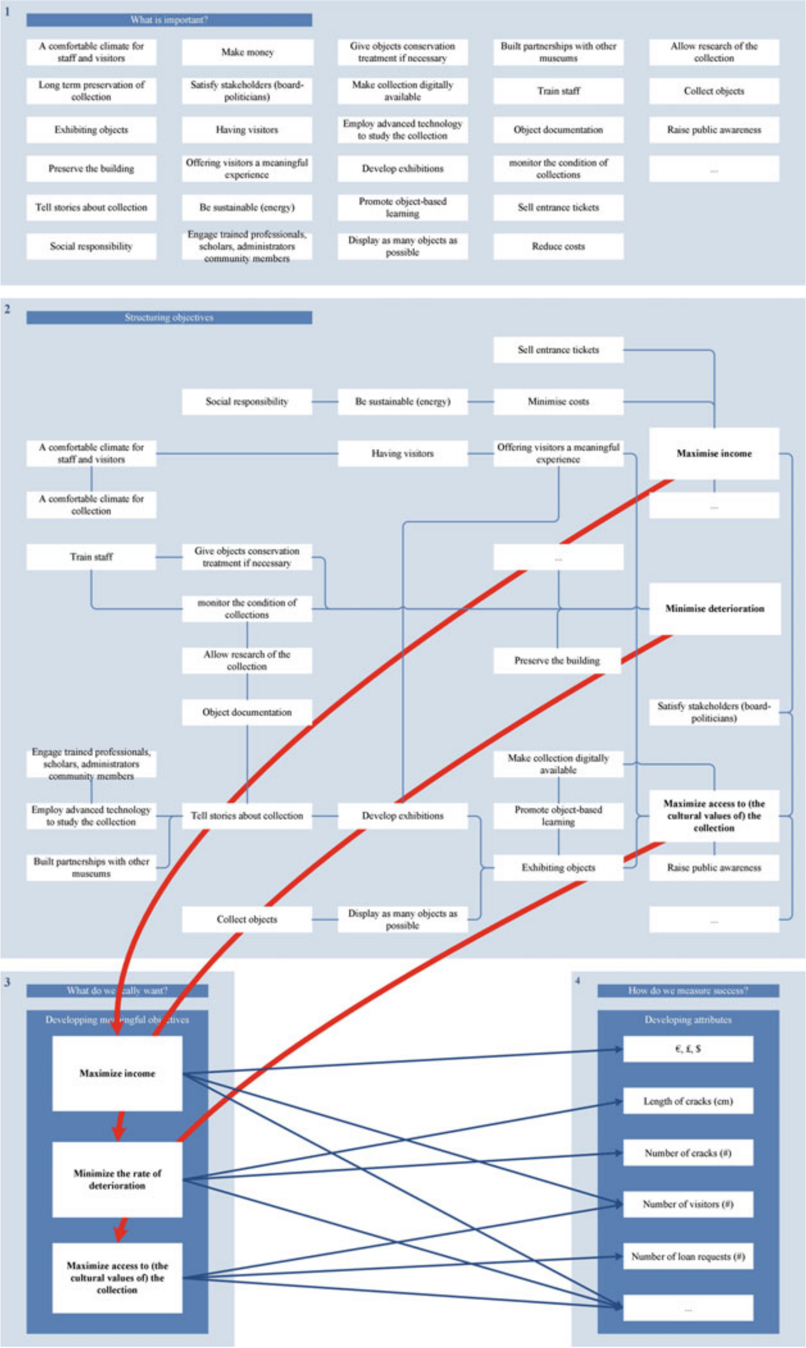

**Fig. 2.3** A schematic presentation of the decision making

## 2.6 Conclusions

Defining what the indoor climate should be, is not an easy process. Considering all the arguments and finding an optimum indoor climate that does justice to all or most of the ambitions, of all or most stakeholders, is time consuming and complex. Every situation is unique and will ask for a specific way of managing the project. Obviously, small decisions with relatively small financial impacts involving only a small part of the collection (value) can generally be agreed upon more easily than projects that involve major building work, that have an impact on most of the collection (value) and require a large budget.

In Fig. 2.3 a schematic visualization of the process is provided. Central in this scheme is the relation between 'What are your ambitions?' and 'What are your options?' In this step it is crucial to think outside the box and develop options that can be evaluated and really allow realization of your ambitions.

The final product of this first step is a list of objectives that will help you in preparing and making the decision at hand. The list should not be too comprehensive, but also not too short. It should be clear which objectives are the most important ones.

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# Chapter 3
# Step 2: Valuing Heritage Assets

**Abstract** Before optimizing the indoor climate by implementing risk mitigation measures, it is essential to understand the loss of value to both the building and moveable collection by the current climate, and to compare this with the potential loss in value by implementing the intended alterations.

Cultural heritage management changed from managing material aspects of collections and monuments or sites, to the management of their cultural significance. To describe this significance it is necessary to understand the combination of cultural values. Moreover, evaluation of value change requires a more quantitative approach to the significance. The relative value of each component will have to be determined.

Implementation of a climate strategy will result in value changes to both the building and collection. Looking at the relationship between the cultural value of the building and that of the moveable collection is the first step in identifying the general climate strategy. The central question to be answered is: "Is the moveable collection related to (the history of) the building?"

A value assessment of a theoretical collection is provided to help illustrate the process.

**Keywords** Loss of value • Cultural significance • Valuation framework • Valuation process • Value classification

## 3.1 Introduction

We care for heritage assets (moveable, immovable, intangible) and we are willing to invest time and money to save them for future generations. We provide optimal protection in times of war (see Chap. 1) and do our utmost to reduce the slow (photo)chemical processes that change the materials.

But why are we interested in these assets and why do we feel that these should also be made available to future generations? Obviously, the importance of these assets is related to a certain significance that they have: they are related to important people in the past (historic value); they are of exquisite elegance (artistic value); they contain information that could be of use (information value); there is only one (uniqueness); they provide a specific sensation and emotion (experience value);

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they are related to a specific (ethnic) group (social value) and / or they represent a certain time, place or style (representation value); they have cultural value!

To describe the significance of an object or collection, i.e. 'the object' it is necessary to understand the different values that combine to give the overall importance. It is this significance that we would like to preserve. So preservation of collections has moved over time from the management of material change to managing the change of values. By identifying the most important values within any heritage asset it is possible to make value based decisions about its use, preservation or development. In short, the essential principles of collection management involve understanding the heritage values and any possible alterations so that decisions about change can be reasonable, transparent and consistent (English Heritage 2008). This reasoning also applies to the management of climate risks. Especially when the measures to reduce risks to the moveable collection, or to improve human comfort levels, require extensive modifications to the historic building (see Fig. 3.1). The New Orleans Charter (APT/AIC 1992) was the result of two symposia on 'Museums in Historic Buildings' held in Quebec in 1990 and in New Orleans in 1991. The charter, widely adopted since 1992, states ten points to help balance the needs for objects of cultural value in structures of cultural value, such as:

- The unique character of both the historic structure and artefacts should be preserved
- Measures which promote the preservation of either the historic structure or the artefacts, at the expense of the other, should not be considered

It is thus essential, to carefully consider how any potential measure to preserve the value of one, will influence the value of the other. Therefore it seems logical to identify the way values of one relate to, or depend on, the values of the other.

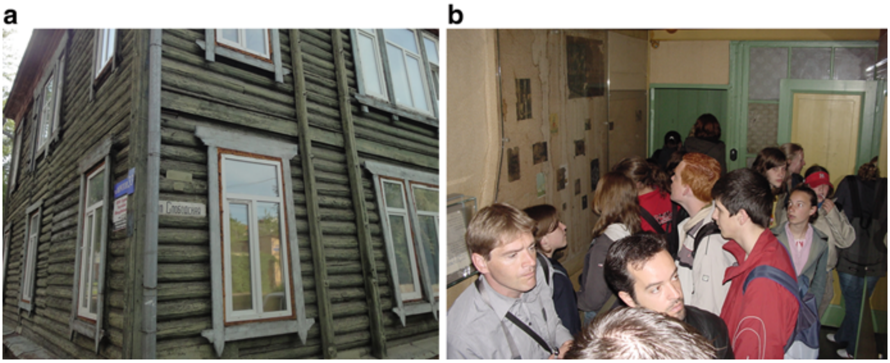


**Fig. 3.1** A traditional Siberian house in Omsk that was modernized by installing double glazed windows, changing the architectural value (**a**). Anne's room in the Anne Frank House where experience value is influenced by the amount of visitors and the Plexiglas plates in front of the original pictures on the wall (**b**)

## 3.2 Valuing the Building

The valuation methodology for (historic) buildings was developed much earlier than that for moveable collections or for intangible heritage assets, such as traditions. Many countries developed a strict set of criteria to separate the important historic, from just old, buildings. Historic properties generally have legal or statutory protection because of their cultural and economic importance.

Valuing a building generally starts with a historic building valuation. The cultural, architectural, and historic construction values, as well as the ensemble and town-planning values, are assessed in terms of rarity and authenticity. Especially authenticity is important, as it drives many decisions relating to conservation and restoration treatments of buildings. In 1994 the definitions and concepts of authenticity were extended to: authenticity of form and design, of material substance, of function and use, and of techniques, traditions and process (ICOMOS 1994). In 1995 the Nara document was adopted. It stated that:

> All judgments about values attributed to cultural properties as well as the credibility of related information sources may differ from culture to culture, and even within the same culture. It is thus not possible to base judgments of values and authenticity within fixed criteria. On the contrary, the respect due to all cultures requires that heritage properties must be considered and judged within the cultural contexts to which they belong.

Generally one can say that those parts of the building that have most of these values should be treated with great care. Ideally these most valued parts of the building should be left unaltered. In addition to the historic building valuation, the ‘changeability’ of a historic or listed building can be determined as a numerical coefficient (Van de Ven 2011). This coefficient is part of a wider assessment method to balance sustainability measures against heritage values. The estimation of this coefficient takes into account what is feasible within a historic building based on its heritage values. In this method preserving important heritage values in buildings of outstanding cultural interest, can compensate for lower levels of environmental gain.

## 3.3 Values

Cultural heritage management changed from managing material aspects of monuments, groups of buildings or sites, to the cultural significance they have, both tangible and intangible. Cultural heritage managers are managing the change of significance. It is important to see that this significance is the sum of all values, but that there are different valuation systems. In order to understand and record the potential change of cultural values caused by preventive conservation measures, a document can be produced in which the different values of the building and collection are described. Documenting the values allows some objectiveness in an assessment that is by its nature subjective. Obviously, the available information, such as the vision and mission of the museum, the historic building valuation, and collection planning, should be used to form a basis for this value description in a so-called *statement of significance* (Russell and Winkworth 2001). In a statement of significance the different key values that an object (collection and building) has for past and current generations are described. Since future generations may describe the significance of heritage objects differently by using a different reference framework and a different perspective, other values may also be of importance. But at least a valuation provides a start point for value based decision making to cope with current issues.

A statement of significance for an object contains different elements such as context, history, and use. In the Burra Charter, cultural significance is defined as the aesthetic, historic, scientific, social or spiritual value for past, present and future generation (Burra Charter 2013). These values are embodied in the place itself, its fabric, setting, use, associations, meanings, records, related places and the related objects. In the specific case of ensembles, the statement of significance must reflect the therein implicit values for all stakeholders, with attention to intangible aspects. The relative importance of the different parts to the whole also needs to be interpreted (Meul 2008).

The Cultural Heritage Agency of the Netherlands (RCE) developed a valuation framework to assist cultural heritage professionals to value their collections (RCE 2014). In six steps the user is guided through the valuation process:

- Describing the reason to assess values: why undertake the assessment? What is the decision to be made?
- Establishing the context: who and what? Today, not only heritage experts are allowed to make valuations, different stakeholders (including the broader public) can be involved.
- Setting the criteria. Which of the values are most important for the decision being discussed?
- Scoring and developing arguments to explain the scoring. Starting with annotations such as, high, medium and low, a relative ranking of values can be made for different (sub)collections.
- Evaluating the scores.
- Making a decision. Investigate how the outcome of the decision influences the values and pay special attention to the highest values and the biggest changes.

The four valuation methods discussed in this chapter are presented in Table 3.1.

**Table 3.1** Different valuation methods with different criteria

| | |
|---|---|
| Significance | *Primary criteria*: historic/artistic or aesthetic/scientific or research potential/ social or spiritual |
| | *Comparative criteria*: provenance/rarity or representativeness/condition or completeness/interpretive capacity |
| English Heritage | Evidential/historical/aesthetic/communal |
| | Rarity/representativeness/aesthetic appeal/integrity/associations |
| Burra charter | Aesthetic/historic/scientific/social or spiritual |
| RCE | *Features*: condition/ensemble/provenance/rarity |
| | *Cultural historic*: historic/artistic/information |
| | *Social*: social/experience |
| | *Use*: museum presentation/economic |
| | *Additional*: free to choose |

## 3.4 Value Classification

Some heritage institutions have already adopted a valuation method to assess the relative significance of their moveable collections. Collections are divided into different value classes based on their significance to the museum collection plan:

1. The most important objects (i.e. heritage assets) in the museum collection; the showpieces, or the objects that are usually on permanent display, sometimes called the 'treasures';
2. Objects that form the core collection, i.e. that contribute to an active museum and collection policy. This is the collection in the museum gallery or in storage, from which objects are used for exhibitions, and are regularly requested for loans to other institutions;
3. Objects belonging to the stored or support collection, but which do fit within the objectives of the museum and are not eligible for de-accessioning. It could be, for instance, a collection having an archival character that is mainly interesting for researchers, or a collection to which much effort has been dedicated in the past, but that now is no longer accessed or used;
4. Objects that do not fit within the objectives of the museum and for which, in principle, another destination is being sought (see Fig. 3.2).

Value categories help identify where potentially the largest loss of value can be expected (prior to taking into account the susceptibility of the heritage assets within the value categories).

The Library of Congress developed and implemented a (business) risk method based on the value and susceptibility of its collections (Price and Smith 2000). The Library uses category names of precious metals that describe groups of items in the

**Fig. 3.2** A museum object without clear documentation and meaning for the collection, will probably be of low value to the collection

collections by degree of tolerance for risk. The Library defined each group as follows:

- *Platinum* includes the Library's most priceless items. The Treasures, a small group of the Library's most precious items, such as the Gutenberg Bible, are the archetypal components of this category.
- *Gold* includes rare items that have exorbitant replacement cost, high market value, and significant cultural, historical, or object importance. This includes first editions and rare books, daguerreotypes, manuscript maps, and wax cylinder recordings.
- *Silver* includes items that require special handling and items at particularly high risk of theft, such as computer software, popular titles in print, videos, and compact discs.
- *Bronze* includes items served without special restrictions in the Library's reading rooms and materials that may be loaned without stringent restrictions.
- *Copper* includes items the Library does not intend to retain but holds while deciding; for example, items that may be used for its exchange and gift programs.

## 3.5 Values and Optimizing the Indoor Climate

Before making any alterations to an indoor climate, it is essential to understand the loss of value (to both the building and moveable collection) by the current climate, and to compare this with the potential loss in value that would occur by implementing the intended alterations. This assessment of the change in values would be a strong argument during the decision making process.

Since implementation of conservation measures, such as climate control to reduce the climate risks to moveable heritage, entails some degree of damage or adverse effects to the material and intangible aspects of a museum (or historic house), the values of the movable heritage (collection) as it were, must be 'weighed' against the values of the building. Similar to the building and collection value ratios presented for Eldon House and Glanmore site to balance conservation decisions (Karsten et al. 2012). The relationship between the building and the collection plays an important role herein. Therefore, the connection between the different elements (movable heritage, interior finish, and building), as well as how this has been reached, should be made explicit. Are these elements inextricably connected to each other, constituting an ensemble or a so-called *Gesamtkunstwerk*? Has the collection been brought to a building that subsequently acquired the function of a museum? Or does the collection serve as decoration to the building?

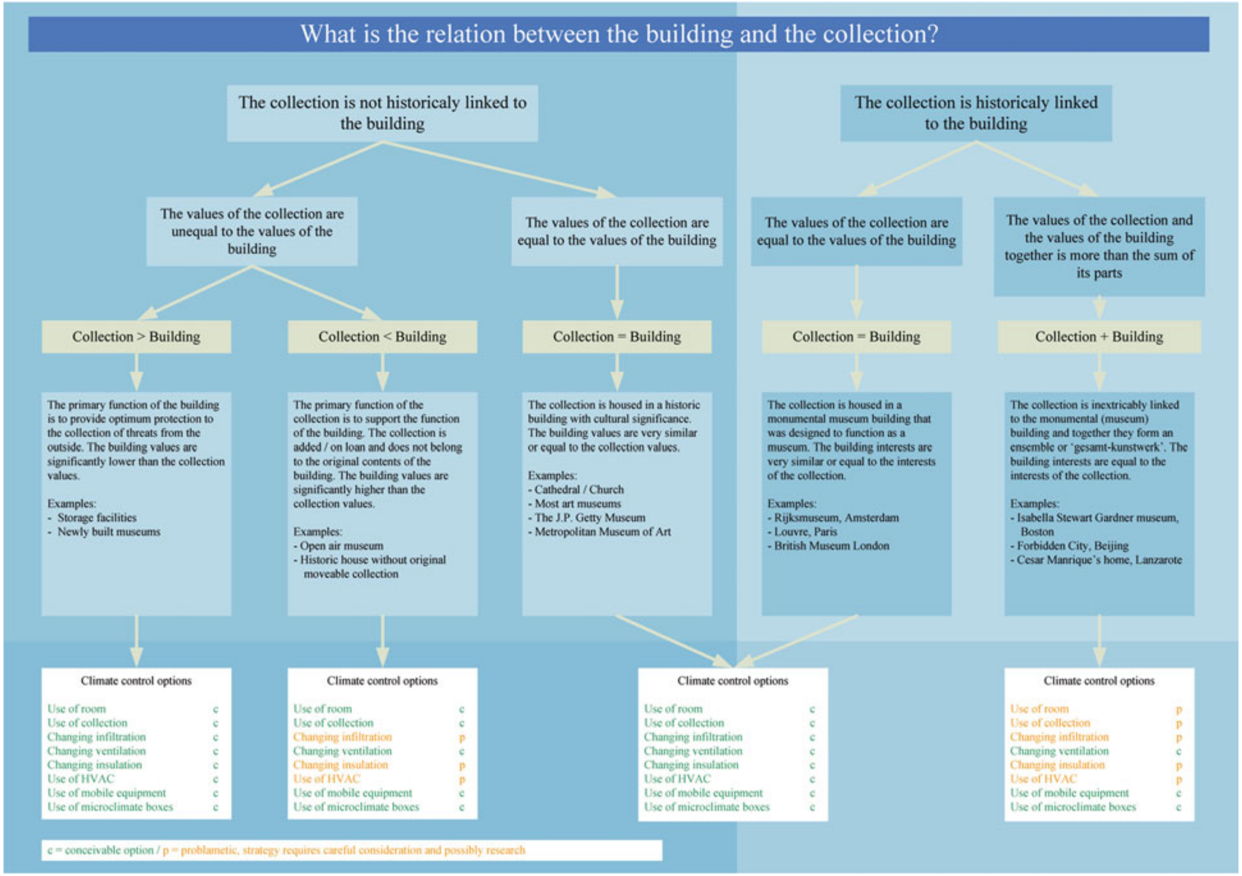
This comparison between the value of the building and that of the collection, or preferably between the potential loss of value to the building and the collection, is one of the factors involved in the choice of a climate control strategy. The concept of 'value' and 'loss of value' encompasses all types of values that play a role in determining the significance of the building and the collection. These include, for instance, cultural, educational, financial, historic, experience, uniqueness, and ensemble values. The extent to which these values contribute to the overall valuation will depend on each specific situation.

Even in cases where a valuation of the building is not necessary it may still be very useful to do it for the collection. The overall goal of preservation, generally, is to achieve the smallest loss of value of the collection given the boundary conditions of knowledge, money and capacity. This may include, for instance, that a control strategy is developed that targets minimizing loss by protecting only the most valuable and the most vulnerable parts of the collection. This implicitly means relaxing the indoor climate for the less valuable and/or less susceptible collection units!

Weighing the building values against the collection values raises the question if, and how the movable heritage (collection) is linked to the building. In Fig. 3.3 a relational scheme is presented, to sketch the different ways the value of the building and of the moveable collection influences the possible decision making in relation to climate control.

The first question that needs to be addressed is: is the moveable collection related to (history of) the building? If not, we are left with three options: the moveable collection is more valuable than the building, or vice versa, or they are of more or less equal value.

If the building is of no cultural significance its primary function is most likely the protection of the moveable collection stored or shown inside. Measures to reduce for example climate risks with adaptations to the building structure will probably result in a very limited, to no loss, of cultural value of the building and are probably easily accepted. The decision making is controlled by the significance of the moveable collection that completely overrules that of the building.



The primary function of the building is to provide optimum protection to the collection of threats from the outside. The building values are significantly lower than the collection values.

Examples:
- Storage facilities
- Newly built museums

The primary function of the collection is to support the function of the building. The collection is added / on loan and does not belong to the original contents of the building. The building values are significantly higher than the collection values.

Examples:
- Open air museum
- Historic house without original moveable collection

The collection is housed in a historic building with cultural significance. The building values are very similar or equal to the collection values.

Examples:
- Cathedral / Church
- Most art museums
- The J.P. Getty Museum
- Metropolitan Museum of Art

The collection is housed in a monumental museum building that was designed to function as a museum. The building interests are very similar or equal to the interests of the collection.

Examples:
- Rijksmuseum, Amsterdam
- Louvre, Paris
- British Museum London

The collection is inextricably linked to the monumental (museum) building and together they form an ensemble or 'gesamt-kunstwerk'. The building interests are equal to the interests of the collection.

Examples:
- Isabella Stewart Gardner museum, Boston
- Forbidden City, Beijing
- Cesar Manrique's home, Lanzarote

**Fig. 3.3** Schematic overview of the relation between the value of the building and collection, including an indication of possibilities for climate control

If the building is much more valuable than the collection, e.g. in an open air museum, then the decision making will most likely be in favor of preserving the building values and accepting (some) loss of value to the moveable collection. Implementation of an air conditioning system that involves placing ducts will probably be very troublesome and only reversible, non-evasive measures should be considered.

It becomes more difficult if the value of the building and that of the collection are similar. Being equally important, when one seeks to minimize the overall loss of value, both the building and the collection need to be protected against changes that will result in a (significant) loss of value to them.

If the answer to the question above is yes, there are only two possibilities: the moveable collection and building are of similar value or, the values of the building and moveable collection together are more than the sum of its parts. In both cases decision making is quite complicated. Much value can be lost from both the building and the moveable collection by adapting the building or adapting the collection. Especially when the value of the building and collection considered together is bigger than the sum of its parts; an ensemble. In these cases both the building and the collection have an important share in the significance of the whole, which means that changing one of them may result in a large loss of value. In such cases, modifications will often (if not always) result in a relatively large loss of experience and authenticity and/or historic value.

This relation between the cultural value of the building and that of the moveable collection can be a first step in identifying the general climate strategy (if climate risks are indeed so high, they need to be reduced!). There are different climate control strategies that have different impacts on the significance (in no particular order):

- *Use*. By controlling visitor flow and dwelling times, it is possible to reduce disturbances of the indoor climate to a certain extent. Historic interiors that are also (frequently) used for events (weddings, conferences, meetings, dinners etc.), a strict control of the number of users, the types of activities, and the season in which they are allowed to take place can be critically (re)considered. Susceptible objects can be temporarily relocated in less critical rooms or spaces.
- *Improving the physical properties of the building envelope*. This aims at minimizing the influence of the outdoor conditions on the indoor climate. For instance, through insulation and limiting infiltration, filling cracks and openings in the façade and the roof, making windows and doors airtight, and installing draught lobbies in exterior doors. In many cases this would be the first step towards improving the indoor climate. Depending on the required interventions, however, this may imply extensive rebuilding or structural alteration. Reversible solutions should preferably be adopted.
- *Microclimate systems*. These are used to provide (passive) protection against incorrect environmental conditions around the object. As a result, the object can no longer be openly displayed. Examples include microclimate boxes and (actively or passively climate controlled) display cases. No rebuilding or

structural modifications to the building is/are required. However, the introduction of a glass barrier between observer and object used to be very problematic (Eastlake et al. 2013), but since the introduction of non-reflective safety glass it has become widely used in many museums around the world.

- *Moisture buffering*. Using finishing materials on interior walls that are capable of absorbing and releasing moisture, such as plaster (without a moisture barrier coating!), it is possible to minimize relative humidity fluctuations to a certain extent. Modifications on walls are typically accompanied by significant changes in the experience value or perception of visitors, and may involve extensive rebuilding or structural alteration. For storage however, high density packing of objects could be considered.
- *Heating and cooling*. The indoor temperature is controlled by means of a heating and/or cooling device. Typical heating strategies involve central heating, underfloor heating, electrical heating, or even using hot air (especially in churches). Depending on the selected option this may require heavy rebuilding or structural alteration. For cooling, air conditioning is often used. In many cases the historic values are changed by the devices needed to transport and produce the hot or cold air. Present comfort levels are very different to the past, a cooled historic interior in summer is experienced quite differently and a uniformly heated house did not exist in the nineteenth century.
- *Portable humidity equipment*. Mobile humidifiers and dehumidifiers can be used locally at a room level to achieve some degree of control over the relative humidity. The major advantage of this type of measure is that it can often be implemented without modifications to the building. Due to their modern plastic appearance and size this type of equipment often negatively affects the way visitors experience a room.
- *Ventilation*. The indoor climate can be positively influenced to a limited extent through the (active) admission of (filtered) outdoor air when the outdoor air is of a better quality than the air inside.
- *Installing a permanent climate control system*. This is used to achieve full climate control by means of an all-air HVAC system that regulates the indoor relative humidity and temperature. It involves the placement of air distribution ducts to transport (un)conditioned air and water pipes for humidification. Dehumidification by cooling requires a water drainage system. Placing ducts, tubes and pipes means a major intervention in the building, with a high potential loss of historic and architectural value (Fig. 3.4).

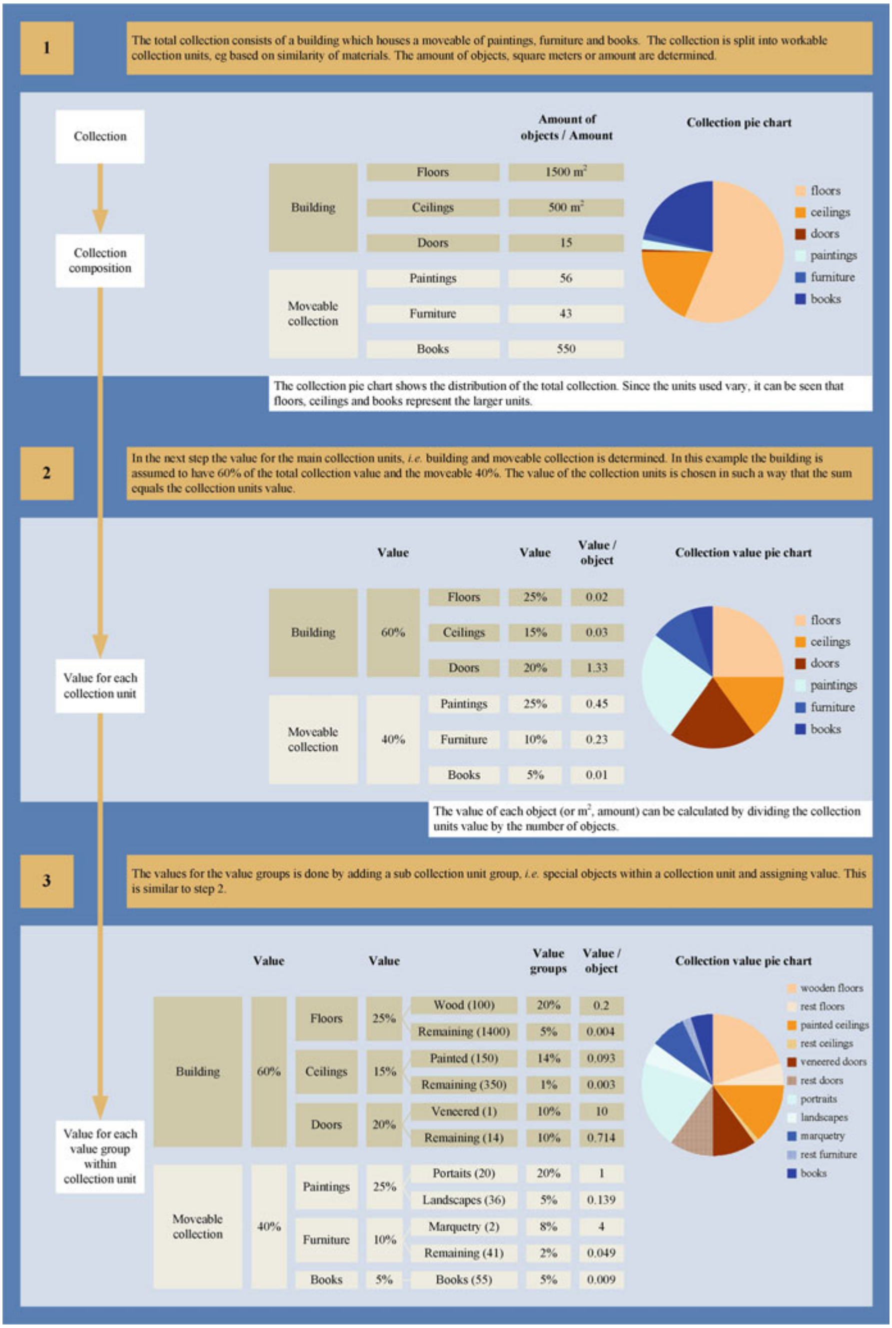
The extent to which the different values of the building and/or the collection will change as a result of implementing a given measure depends on how this is carried out. In Fig. 3.3, different possible measures are marked with a $p$ or a $c$ to indicate whether they are likely to be problematic ($p$) or conceivable ($c$), depending on the ratio between the value of the building and the value of the collection. In other words: $c$ represents a choice that is conceivable, while $p$ indicates an option that cannot be excluded but requires (much) attention in its elaboration.

**Fig. 3.4** Ducts require a lot of space, when placed in a historic room and covered from view by painted MDF, the historic and experience values will change significantly

## 3.6 The Valuing Process

The implementation of measures should be discussed within an interdisciplinary team of professionals (architect, installation engineer, facility manager, curator, architectural historian) who will consider all aspects of value and value loss in order to arrive at an optimal result. Good planning of the entire process, from the initial phase until its conclusion, is essential. This will allow an early identification of which experts should be brought together, at which moments, during the decision making process. Interim adjustments or changes in initial assumptions along the process should, ideally, always be discussed by the professionals involved. The goal is to jointly design integrated solutions. It should be noted that, in practice, the decision making is often driven by the availability of time. Some degree of flexibility is therefore necessary.

It is advisable to begin the valuation process by compiling all relevant information, then to engage in discussions with all stakeholders. A valuation (concept statement of significance) can be jointly produced, which would serve as a basis throughout the decision making process. In the valuation document, an attempt should be made to define the distribution of the different values over the collection



The total collection consists of a building which houses a moveable of paintings, furniture and books. The collection is split into workable collection units, eg based on similarity of materials. The amount of objects, square meters or amount are determined.

| | | Amount of objects / Amount |
|---|---|---|
| Building | Floors | 1500 $m^2$ |
| | Ceilings | 500 $m^2$ |
| | Doors | 15 |
| Moveable collection | Paintings | 56 |
| | Furniture | 43 |
| | Books | 550 |

The collection pie chart shows the distribution of the total collection. Since the units used vary, it can be seen that floors, ceilings and books represent the larger units.

In the next step the value for the main collection units, *i.e.* building and moveable collection is determined. In this example the building is assumed to have 60% of the total collection value and the moveable 40%. The value of the collection units is chosen in such a way that the sum equals the collection units value.

| | Value | | Value | Value / object |
|---|---|---|---|---|
| Building | 60% | Floors | 25% | 0.02 |
| | | Ceilings | 15% | 0.03 |
| | | Doors | 20% | 1.33 |
| Moveable collection | 40% | Paintings | 25% | 0.45 |
| | | Furniture | 10% | 0.23 |
| | | Books | 5% | 0.01 |

The value of each object (or $m^2$, amount) can be calculated by dividing the collection units value by the number of objects.

The values for the value groups is done by adding a sub collection unit group, *i.e.* special objects within a collection unit and assigning value. This is similar to step 2.

| | Value | | Value | | Value groups | Value / object |
|---|---|---|---|---|---|---|
| Building | 60% | Floors | 25% | Wood (100) | 20% | 0.2 |
| | | | | Remaining (1400) | 5% | 0.004 |
| | | Ceilings | 15% | Painted (150) | 14% | 0.093 |
| | | | | Remaining (350) | 1% | 0.003 |
| | | Doors | 20% | Veneered (1) | 10% | 10 |
| | | | | Remaining (14) | 10% | 0.714 |
| Moveable collection | 40% | Paintings | 25% | Portaits (20) | 20% | 1 |
| | | | | Landscapes (36) | 5% | 0.139 |
| | | Furniture | 10% | Marquetry (2) | 8% | 4 |
| | | | | Remaining (41) | 2% | 0.049 |
| | | Books | 5% | Books (55) | 5% | 0.009 |

**Fig. 3.5** An example of a theoretical value assessment

units and/or the building. For this quantification there is no systematic methodology available.

Obviously, not all decisions related to managing indoor climate risks require such an extensive analysis of the significance of the heritage assets involved. It should be noted however that in many cases the climate risks are only managed by making large decisions every 30–50 years when a building is extensively adapted and made ready for the next generation. Since large amounts of money are involved and much cultural value can potentially be lost, it seems logical to make these value based decisions assessing the significance of the assets affected.

A simple example of a value assessment is provided in Fig. 3.5. It concerns a theoretical collection of paintings, furniture and books in a building with some doors, ceilings and floors of cultural value. The process starts with identification of the collection composition, i.e. describing the collection units (here based on material aspects).

In the second step the value of the building and the moveable collection is determined. The amount of value for the building is subsequently divided over the immoveable collection units and the same is done for the moveable collection. In this case 40 % of the value is divided over the paintings (25 %), furniture (10 %) and books (5 %). The value per object is calculated by dividing the amount of value, by the amount of objects in that collection unit. In step 3 the values of different (groups of) objects within a collection unit are assessed. As an example, the floors have 25 % of the total collection value, consisting of one important wooden floor and the remaining floors are of average value. The value of the important wooden floor is expressed by assigning 20 % of total collection value and only 5 % to the remaining floors. By dividing the total collection value per sub unit (wooden floor = 20 %), by the surface area of the wooden floor (100 $m^2$), the value per $m^2$ is calculated. By making these calculations, the most valuable objects are easily determined. In this case, the veneered door and the marquetry furniture stand out as highly valuable, while the remaining floors and ceiling are the lowest valued assets per unit.

## 3.7 Conclusions

Valuing collections is like taking a snapshot. Values change in time. The cultural values are developed by the curators doing research on the history, provenance and use of objects. They are giving meaning and produce stories that can be told. Deterioration processes and conservation treatments will change the look and feel of objects and thus their value. The expected lifetime of the value assessment is thus rather limited, but yet essential for decisions to be made.

If the fundamental goal of most, if not all heritage institutes is to give our future generations access to as much cultural value as possible, we will have to manage these values and the change of them. Knowing what they are and knowing which objects contain most of them is paramount.

The result of this step is a list of the collection and it's anatomy that is influenced by the decision to be made. For each of the collection units or objects, the relative (cultural) value is indicated. The collection units and/or objects with the highest value, i.e. the treasures are identified.

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# Chapter 4
# Step 3: Assessing the Climate Risks to the Moveable Collection

**Abstract** Background information on the climate risks to moveable collections is provided. The three damage processes are chemical, mechanical and biological deterioration. Deterioration processes in which moisture plays a role, can take place at any relative humidity. There is not a universally safe, risk-free relative humidity for all materials. The only possible generalization is that a relative humidity above 75 % for a prolonged time is dangerous. As it increases the risk of faster corrosion, sick glass formation, mold growth on organic materials, and the thriving and increased activity of a number of damaging insect species, which might be unacceptable.

Temperature plays an important role in chemical and biological deterioration processes. The rate of chemical reactions increases at higher temperatures. In principle, the lower the temperature, the longer the expected lifetime of objects and thus their usability in a museum context.

The general conclusion to be drawn from the work presented in this chapter is that the strictly controlled museum climates have, since the 1980s, changed to more relaxed specifications. The aim for chemically unstable collections is long-term preservation and acceptance of seasonal changes and broader ranges of short-term fluctuations and gradients. Studying objects in-situ showed that many objects have survived remarkably well in conditions that were far from the classical 'ideal' demonstrating that strict climate specifications for objects is not required per se.

**Keywords** Climate risks • Chemical degradation • Mechanical degradation • Biological degradation • Incorrect relative humidity • Incorrect temperature

## 4.1 Introduction

The composition of the individual objects in the collection, their materials, their construction, and the circumstances to which they have been exposed (including before they were added to the museum collection) determine to what extent specific environmental conditions in the (near) future will cause damage. In this context objects refers to both movable and immovable collection items. Sometimes the fixed parts of the building envelope, such as floor tiles, often not documented as part of the museum collection, can still be important treasures. Depending on the

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susceptibility of the moveable collection, specifications describing use and environmental conditions will have been selected to keep the risks of damage as low as possible.

Robert Waller, working at the Canadian Museum of Nature in Ottawa, developed a Cultural Property Risk Analysis Model (CPRAM) (Waller 2003) as a natural evolution to integrated preventive conservation and the risk assessment thinking provided by Jonathan Ashley-Smith (1999). The CPRAM model provides a structure to identify, quantify, and evaluate risks. Based on this assessment it is possible to establish priorities for the implementation of measures to reduce the relevant risks, and to make well-informed collection management decisions. The methodology considers ten agents of deterioration (see appendix 2) for the identification of risks. Within the context of the museum indoor climate, only two of these agents are discussed: incorrect relative humidity and incorrect temperature. It is obvious that reducing climatic risks is less meaningful when they represent a smaller threat to the collection than other risks.

It is advisable to get an overview, preferably quantitatively, of the different risks affecting the collection to decide whether or not the indoor climate should be changed. For this purpose, a method was developed by the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) in collaboration with the Cultural Heritage Agency of the Netherlands (then ICN, now RCE), the Canadian Conservation Institute (CCI) and the Museum of Nature.

If the results of such a risk analysis show that it is necessary to adjust the indoor climate, the project can start. To ensure that the project will be responsibly implemented from its initiation phase to delivery, a multidisciplinary team should be convened at the different decision making moments to analyze and discuss relevant aspects from different points of view. The advantages of controlling the indoor climate for the movable objects of the collection should always be weighed against the disadvantages of the envisaged measures for other parts of the collection, based on the valuation of the total amount of heritage assets: collection and building (see also step 1). This means that good planning is essential and should be carried out for the entire process, from initiation, to delivery, and through to operation. This is to prevent finished buildings being handed over without the HVAC having being commissioned for use by the building managers. As a result no one can operate the HVAC as no one understands the control system. It also prevents ending up with a climate control system that is not sustainable due to high operation costs. A schedule of requirements should be formulated after it has become clear if there are indoor climate issues related to the collection, the building or the occupants, which will clearly describe how the indoor climate should be changed. Before climate targets can be formulated, however, the climate risks to the collection should be explicitly identified. Herein there are three types of damage process that play a role:

- *Chemical deterioration*. Encompasses all processes in which chemical reactions are the primary cause of decay.

- *Mechanical deterioration*. Encompasses all processes in which materials crack and deform as a result of stresses caused by constrained shrinkage and expansion due to climate fluctuations.
- *Biological deterioration*. Encompasses the processes in which mold growth or insect pest attack results in damage to the collection.

In Chap. 23 of the ASHRAE Handbook (ASHRAE 2013), the indoor climate risks are explained based on these decay processes. In 'Klimaatwerk' (Ankersmit 2009), an approach was chosen based on the generic risks of an incorrect relative humidity and an incorrect temperature. This allows a better integration into the risk management approach. The different relevant effects on different objects and/or materials should be dealt with on a case by case basis. Figure 4.1 shows a schematic overview of the different indoor climate risks and the materials/objects that could possibly be damaged by them, indicating the corresponding pages where the different topics are discussed in more detail.

## 4.2 An Incorrect Relative Humidity

The relative humidity of the air plays an important role in the three decay processes affecting collections. Biological deterioration requires that a certain amount of moisture is present for microorganisms to be active and feed on organic materials, thus causing damage. Among the chemical deterioration processes, hydrolysis and corrosion strongly depend on the relative humidity levels. As a rule of thumb, the higher the relative humidity the faster these two chemical decay processes occur. In the case of mechanical deterioration processes it is mainly the changes in relative humidity with a subsequent change of moisture content and the resulting swelling and shrinking of materials that lead to wear, deformation, and fracture. If the relative humidity becomes too low an irreversible drying (loss of hygroscopicity) may occur in some materials, like parchment (Hansen et al. 1991). Based on these types of deterioration processes, four different situations can be considered:

1. The relative humidity is above 0 %.
2. The relative humidity is above or below a critical value.
3. The relative humidity is above 75 % (damp).
4. The relative humidity fluctuates too much.

It is the material composition and the structural properties of an object that will ultimately define the extent to which it can be damaged (and lose value) by these different incorrect relative humidity processes. All four processes are discussed in more detail below.

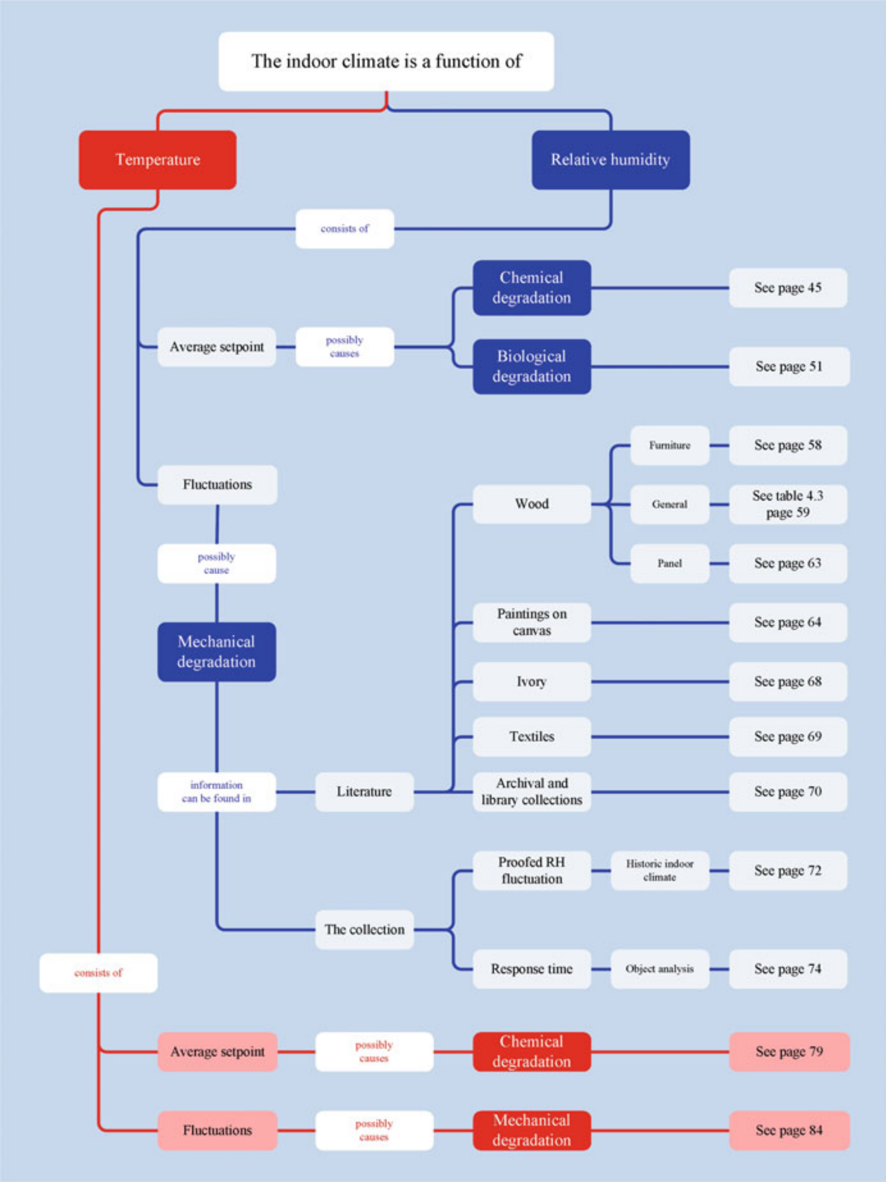

**Fig. 4.1** Schematic overview of the indoor climate threats and the materials/objects that could possibly be damaged, with reference to the corresponding pages for background information

### *4.2.1 The Relative Humidity Is Above 0 %*

Deterioration processes in which moisture plays a role, can take place at any relative humidity. The rate at which these processes occur depends on the sensitivity of the material. It is possible to differentiate between materials with a high, medium, or low chemical stability. The expected lifetime (or rather the predicted time the object can continue to be used or displayed for) for different sensitivity categories is shown in Table 4.2 with examples of objects and materials belonging to each category.

In order to quantify the influence of relative humidity on the rate of different relative humidity-dependent chemical reactions it is useful to express this relationship in an equation. Using data available in the literature on paper degradation, on aging of film materials and magnetic media, and on the yellowing of varnishes it has been shown that the reaction rate depends on a power law of the relative humidity, see Eq. 4.1 (Michalski 2002):

$$k = RH^{1.3} \tag{4.1}$$

In this equation, $k$ is the reaction rate constant ($s^{-1}$), and RH is the relative humidity of the air (dimensionless). From the reaction rate it is possible to derive the expected lifetime or utility time of materials and objects. They are in fact inversely proportional to each other. The relative permanence (RP) of chemically unstable objects can be estimated at any given relative humidity and temperature in relation to a reference relative permanence of 1 at relative humidity = 50 % and T = 20 °C (68 °F). Figure 4.2 shows the line of equal RP at 20 °C (68 °F) for different

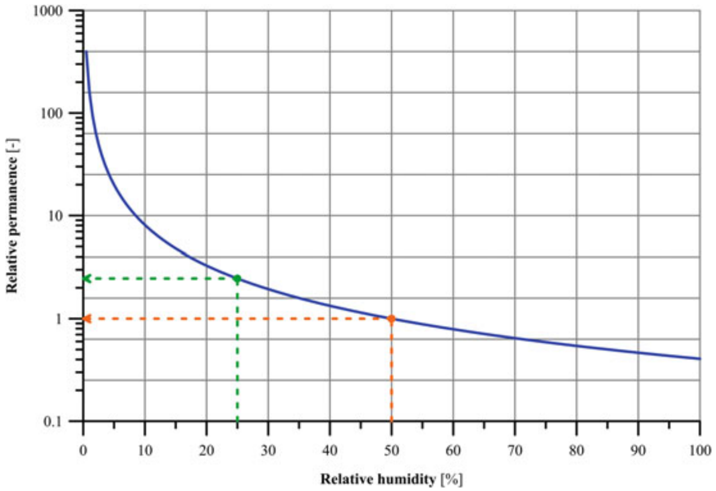

**Fig. 4.2** Expected relative permanence of chemically unstable objects as a function of relative humidity at 20 °C (68 °F). The orange line indicates the bench marked relative permanence of 1 at a relative humidity of 50 % and a temperature of 20 °C (68 °F) (Based on Michalski 2002)

relative humilities. This line is also called an isoperm: a line of equal permanence (Sebera 1994).

It can be seen in the graph that the permanence on the logarithmic vertical axis, increases as the relative humidity decreases. The relative permanence of materials that undergo moisture-dependent chemical degradation reactions approximately doubles as the relative humidity is halved (green dotted line in Fig. 4.2). This means that a chemically unstable collection with an expected lifetime of 30–100 years will experience an increase in permanence by a factor of 2–2.5 if the relative humidity is reduced from 50 % to 25 %. In other words, the expected lifetime of the collection at a relative humidity of 25 % would be 75–250 years. In contrast, when the relative humidity increases the expected permanence decreases. For chemically unstable materials such as acidic paper, a low relative humidity is significantly beneficial for their expected lifetime.

A special group of objects that are generally regarded as objects with low chemical stability are iron-gall ink-corroded documents. These however, constitute an exception. Recent research has shown that the progress of ink-corrosion is very slow under ordinary European climate controlled museum and storage conditions (40 % < RH <60 % and 17 °C (63 °F) < T <22 °C (72 °F)). This can be explained by the fact that there are two different underlying processes that ultimately determine the permanence of this type of documents: the transport of harmful ink components ($H^+$ and $Fe^{2+}$ ions), and their reaction with the cellulosic fibers of the document. It has been shown that objects showing extensive ink-corrosion damage have been exposed to highly humid conditions in the past, e.g. in the tropics or in salt mines during World War II, or have somehow been affected by incidents involving water. These humid conditions have promoted the transport of the (water-soluble) reactive chemical species, which subsequently caused deterioration in different areas of the paper. The greatest risk of damage to this type of objects, therefore, results from exposure to very high relative humidities. This causes the equilibrium moisture content of the paper to increase and, as a result, activates the transport of active iron ions and sulfuric acid from the ink into the adjacent areas and through the paper (Kolar et al. 2006). It seems that there is a relative humidity threshold under which this transport will hardly happen, but above which it will happen very fast. The threshold value has not been precisely determined, but presumably lies above a relative humidity of 65 % (Wilson 2007; Rouchon 2008; Ligterink et al. 2008). A low relative humidity is desirable but not essential for the optimal conservation of this group of objects, the key is ensuring that the relative humidity does not exceed 65 %. The regular hydrolytic decay of the paper, without the influence of the ink, will still proceed at a rate that primarily depends on the type of paper (see Table 4.1).

Hygroscopic materials such as acidic newspaper stored under dry conditions undergo volume changes due to the release of moisture. The extent to which these changes increase the risk of mechanical damage depends on the object and the way it is displayed or stored. It should be decided on a case by case basis if the reduction to the risk of chemical decay outweighs an increase in the risk of mechanical damage. For instance, dry conditions could be beneficial for the conservation of

**Table 4.1** Expected lifetime of different materials belonging to different chemical stability categories (Michalski 2000)

| High chemical stability | Medium chemical stability | Low chemical stability |
|---|---|---|
| Lifetime 300–1,000 years at 20 °C (68 °F) and 50 % relative humidity | Lifetime 100–300 years at 20 °C (68 °F) and 50 % relative humidity | Lifetime 30–100 years at 20 °C (68 °F) and 50 % relative humidity |
| Examples: | Examples: | Examples: |
| Parchment, vellum | Mildly acidic papers (most papers and boards) | Strongly acidic paper (newspaper) |
| Rag paper, not acidified by pollution or sizing | Most black-and-white (silver/gelatin) negatives and films on acetate and nitrate | Leather exposed in the past to acidic pollution |
| | | Poorly processed photographs. |
| | | Most color photographs |
| Alkaline paper | Albumen photographs | Some acetate and some cellulose nitrate films (and negatives) |
| | Some collodion glass negatives | Magnetic media (e.g. video, digital tapes, disks) |
| | Some color photographs on paper, on film | Poorly made optical digital media (CD's) |
| Wood | Well-made optical digital media (CD's) | |
| Most black-and-white (silver/gelatin) photographs or microfiche (on paper, glass, or polyester) | Unstable alkaline glass | |
| Most collodion negatives on glass | | |
| Paint on wood, canvas, or stable paper | | |
| Inorganic materials such as metal, stone, glass | | |

the book block in a parchment binding. However, under these conditions, the binding (Fig. 4.3) would probably not withstand consultation in the reading room without being mechanically damaged. Even though there is some debate about a safe low limit for the relative humidity that will not cause irreversible drying of parchment, 25 % is generally accepted for safely keeping parchment (Hansen et al. 1991).

Metal corrosion is another, very important chemical degradation process. According to Scott (2002, p 61), copper corrosion rates under museum indoor climate conditions can be described by the following function:

$$k = 0.97 \cdot e^{4.6 \cdot RH} \tag{4.2}$$

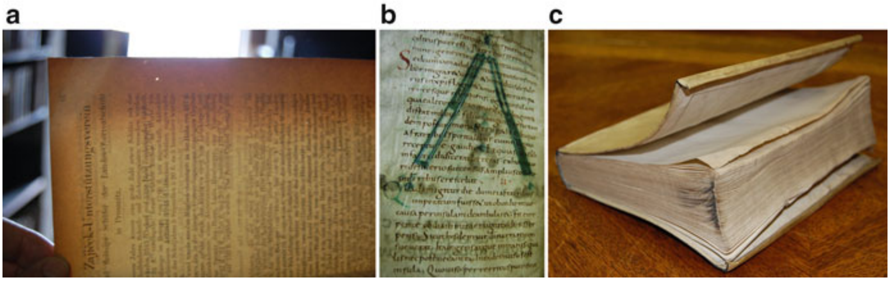

**Fig. 4.3** Paper documents: an acidic paper with moderate chemical stability (**a**); a copper corroded paper artifact with low chemical stability (**b**); book block in a parchment binding under dry conditions (**c**)

where $k$ is the reaction rate constant ($s^{-1}$), and RH is the relative humidity (dimensionless). It is clear that corrosion proceeds faster as the relative humidity increases. At a relative humidity of 75 %, the corrosion rate is approximately three times faster than at 50 % relative humidity. Halving the relative humidity reduces the decay rate by a factor of slightly more than 2. Most corrosion processes proceed rapidly above a relative humidity of 75 %. The main reason is the exponential increase of water adsorption on the metal surface with increasing relative humidity. Therefore, the general principle of 'the drier, the better' is applicable for metals. For some metals, like silver, however, the tarnishing rate as a function of the relative humidity has three correlations between $Ag_2S$ weight increase and RH: $0\,\% < \mathrm{RH} < 30\,\%$ almost linear increase of tarnishing; $30\,\% < \mathrm{RH} < 75\,\%$ constant tarnishing rate; $75\,\% < \mathrm{RH} < 100\,\%$ exponential increase of tarnishing with increasing relative humidity (Drott 1960). The silver tarnishing damage function shows a strong relation with the temperature (Thickett et al. 2013).

It should be noted that the corrosion rate of iron is not only dependent on the relative humidity, but also on the presence of dust particles that can be directly corrosive or indirectly corrosive. High dust levels will enhance corrosion even at relatively low relative humidity (Scott and Eggert 2009, p 112).

The decay of archaeological metal collections as a function of relative humidity depends primarily on the active ions that are present in the corrosion layer. The lifetime of archaeological iron is therefore more strongly dependent on the application (or not) of a conservation treatment to remove active ions than on the conditions under which the objects are kept. Untreated archaeological iron artifacts can corrode completely within a few decades even in very dry environments (Keene 1993). An example of active corrosion is the occurrence of orange iron oxyhydroxides generated from ferrous chloride ($FeCl_2.4H_2O$, $FeCl_2.2H_2O$) present in archaeological iron artifacts recovered from salt-rich environments. The corrosion process is cyclic: chloride ions released by the water-soluble ferrous chloride react with metallic iron converting it into more ferrous chloride. This process can occur even at relative humidities below 20 % (Turgoose 1982). By removing the active chloride ions from these objects corrosion will proceed relatively slowly up to a relative humidity of 55 %. At higher relative humidities, however, it will still be a fast decay process. This process of crystals dissolving at high relative humidity, to form droplets, and again solidifying into hollow spheres at low relative humidity is also known as weeping. Between 0 and 19 % relative humidity the chlorides ($FeCl_2.2H_2O$) are stable as yellow crystals, hydration starts between 19 and 44 % and a pale green solid ($FeCl_2.4H_2O$) is formed. Above 55 % akaganéite and ferrous chloride tetrahydrate are formed as well as a yellow solution (Scott and Eggert 2009, p. 58).

Research by Thickett (2012, p. 185) showed that akaganeite was not formed below a relative humidity of 19 % for most mixtures and below 16.7 % when cuprous chloride is present. Since many iron archaeological finds will contain traces of copper, a relative humidity below 16 % is advised, if possible. Between a relative humidity of 30–35 % the formation rate of akaganeite increases. Depending on post-excavation storage and possible treatment corrosion will not occur below 11 or 16 % relative humidity, the corrosion rate is generally low below 30 % and increases between 30 and 35 % and is fast above 50–60 %.

Archaeological bronze contaminated with chlorides has a complex corrosion mechanism whereby different critical relative humidity values play a role in determining the overall rate of corrosion (Scott 2002).

### *4.2.2 The Relative Humidity Is Above or Below a Critical Value*

In museum collections there can be objects with very specific chemical properties: they will absorb or release moisture at specific relative humidities and, as a result, undergo chemical changes. Typical examples of these types of materials and artifacts are minerals and some archaeological metals. Pyrite, a common contaminant found in fossils, is a mineral that reacts chemically with oxygen and moisture in the air at a relative humidity above 60 %. The reaction product has a larger volume than pyrite, so as it reacts, it expands, which typically causes specimens containing pyrite to crack into pieces and fall apart (Waller 1992).

Most glass is more or less insensitive to relative humidity. However, there is one important exception: the so-called unstable alkaline glass. In this type of glass, sodium and potassium ions from the glass matrix are replaced by hydrogen ions from moisture and form solutions of the respective hydroxides. These solutions absorb carbon dioxide ($CO_2$) from the air, which reacts with the alkali metal ions to form the corresponding metal carbonates. Subsequent reactions with possible different harmful gasses can lead to the formation of new organic and inorganic compounds (see Fig. 4.4). A wide range of hydroxides and salts are found on unstable glass. Typical salts include carbonate, bicarbonate, chloride, sulfate, nitrate, formate, and acetate. These compounds occur as crystals under their respective deliquescence points, and as highly reactive solutions above that relative humidity. Each compound has its specific deliquescence point: 5 % relative

**Fig. 4.4** A eighteenth century venetian glass with white crystalline efflorescence, composed of 80 % calcium sulfate ($CaSO_4$) and 20 % potassium hydrogen sulfate hydrate ($KH_3(SO_4)_2.2H_2O$)

humidity for potassium hydroxide, 6 % relative humidity for sodium hydroxide, 44 % relative humidity for potassium carbonate, 91 % relative humidity for sodium carbonate, 32 % for calcium chloride and 50–55 % sodium formate. Salt efflorescence can be avoided by keeping the collection at a relative humidity that is as constant as possible, preferably under the deliquescence point of the occurring salts. In practice most glass contains a mixture of salts, which affects the deliquescence point and can lead to multiple relative humidity points at which some salts are in solution and some are crystalline. Therefore a stable relative humidity seems to be the best option. Different recommendations for a safe relative humidity to store or exhibit unstable glass can be found in the literature, ranging from a relative humidity of 38 % ± 3 % to 45−55 % (Kunicki-Goldfinger 2008). A low, stable relative humidity around 40 % seems optimal.

In general, the properties of hygroscopic materials change gradually as the relative humidity increases or decreases. That is not the case, however, for how a relative humidity change causes damage to salt-loaded tile collections (Halsberghe et al. 2005). The expansion that takes place upon the formation of crystals from the salt solution causes stress with possible cracking of glazing and cracking of tiles. For certain salts, there are very narrow ranges of relative humidity below or above which the state of the salt changes. Crystallization (efflorescence) or dissolution (deliquescence) of these salts occur at specific relative humidity values. For instance, sodium chloride crystals (common table salt, NaCl) form a solution by absorbing moisture from the air at relative humidities above 76 %. A practical application of this phenomenon is the use of a pressure sensitive tape with table salt crystals stick to it as a relative humidity indicator. Deliquescence of the salt crystals indicates that the relative humidity is or has been locally higher than 76 %.

For mineral collections containing hydrated minerals there is not really a risk-free relative humidity range (Waller 1992). A stable relative humidity without fluctuations that would cause changes in the hydration state of the minerals (by removing or adding water of crystallization) is the ideal option. The optimal relative humidity value should be defined on a case by case basis, depending on the mineral. Preferably this relative humidity should be low enough to prevent deliquescence.

This variety of critical relative humidities shows that there is not a universally safe, risk-free relative humidity for all materials. The only possible generalization is that a relative humidity above 75 % is always dangerous, as described below. Where specific materials require specific conditions, the best option for mixed collections is to create these specific relative humidities in the close surroundings of the object by using microclimate strategies.

### *4.2.3 The Relative Humidity Is Above 75 %*

Mold grows on substrates that contain enough moisture and nutrients. These substrates are usually organic materials, but can also be inorganic materials whose surfaces contain enough dirt or grease to provide a growth medium for the microorganisms (see Fig. 4.5). The amount of water available on the surface, or more strictly speaking the water activity, however, is a decisive factor for the development of mold. The water activity depends on the relative humidity of the surrounding air and on the temperature of the surface. If the surface and the surrounding air have the same temperature, then the relative humidity can be used as an indicator of the chance of mold development (Adan 1994). An alternative way to estimate this risk is to relate the surface temperature to the indoor absolute humidity using a psychrometric chart (see Fig. 1.1), which gives the relative humidity at the surface. Most fungal spores found in collections will only germinate and grow into mold colonies at relative humidities above 70 %. Their growth rate depends strongly on the surrounding relative humidity and temperature. At higher relative humidities the risk of damage to the collection by pests also increases (Brokerhof et al. 2007).

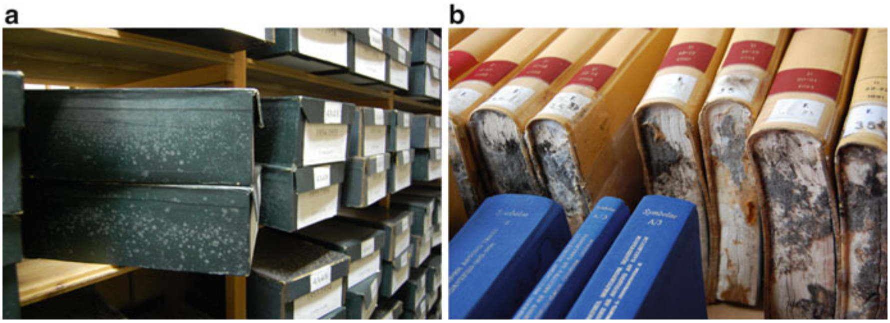

**Fig. 4.5** Mold growth in a collection: slowly formed mold colonies on boxes due to prolonged exposure to an excessively high relative humidity (**a**). Relatively fast mold growth on books affected by a water incident (**b**)

Mold growth is modeled as a function of relative humidity, temperature and type of building material (substrate), i.e. bio degradable and porous. This model visualizes a calculated cumulative growth under different climatic conditions during prolonged time periods (Sedlbauer 2001), using measured relative humidity and temperature as inputs.

The basis for this model are the so-called isopleths, i.e. lines of equal spore germination times or equal growth that show at which conditions fungal growth occurs and if so, at what rate. The germination time, i.e. the time needed for spores to become active, is given in Fig. 4.6. Lines of equal germination time, so-called isolines are shown. The low limit of germination is marked LIM. After germination, molds grow. In the two graphs on the right in Fig. 4.6 growth rates for combinations of temperature and humidity are presented.

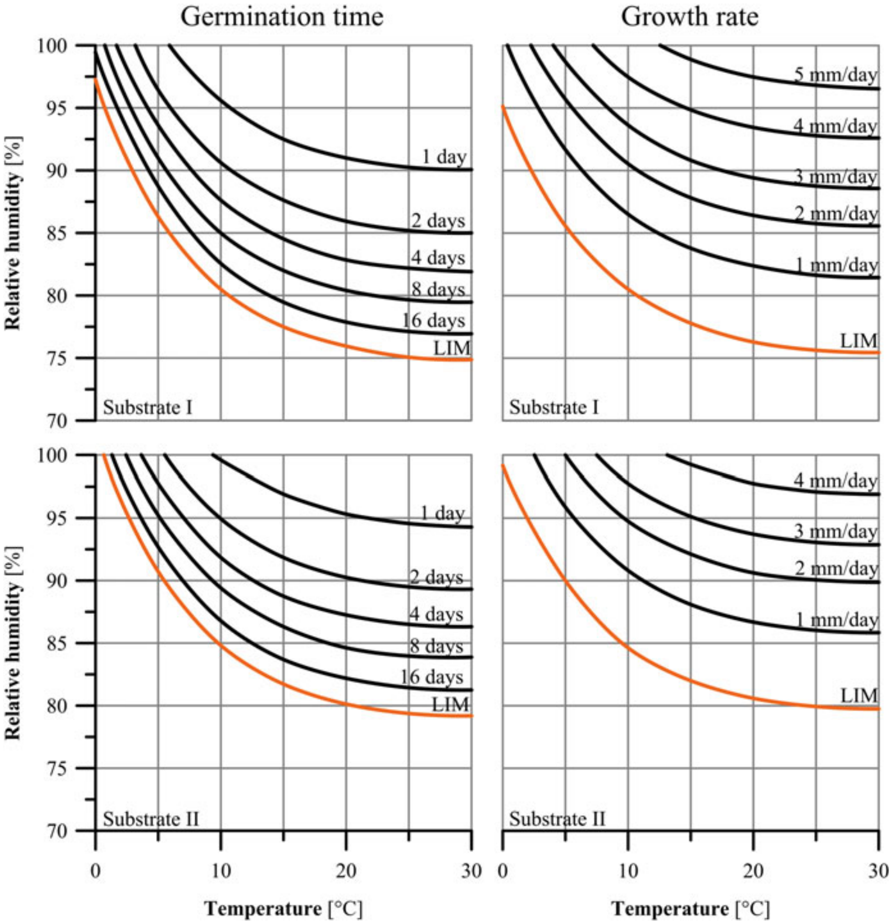

**Fig. 4.6** Generalized isopleth system for spore germination and mycelium growth on building materials (Sedlbauer 2001)

Figure 4.6 shows spore germination (left) and mycelium growth rates (right) as a function of the relative humidity and the temperature for two types of substrate, substrate I the biodegradable building materials like wallpaper, plaster and cardboard and substrate II the porous materials such as renderings, or mineral building materials. The top graphs (substrate I) are valid for surface materials that are biologically recyclable and provide nutrients for mold (type I). The bottom graphs correspond to non-biologically recyclable porous materials (type II), which are capable of holding nutrients in the form of dust.

Figure 4.7 shows a summary of the research done on mold growth, indicating safe and dangerous temperature and relative humidities. A very conservative estimate of the lowest relative humidity at which mold growth could still occur is therefore 60 %. At 65 % relative humidity it takes about 3 years before mold becomes visible, and at 70 % relative humidity the time to onset of visible mold is reduced to a couple of months. It is known that the DNA helix of fungi collapses at a relative humidity below 55 % (Beuchat 1987). This means if the collection is exposed to a relative humidity of 70 % for a short period and then to a dry period, the risk of mold growth is negligible. At relative humidities above 70 %, however, the risk becomes considerable.

So where does the reduction of the mold risk to objects begin? Restriction of mold germination is an obvious primary control of mold harm, restraining subsequent growth is a close second and preventing propagules is a third. So an obvious

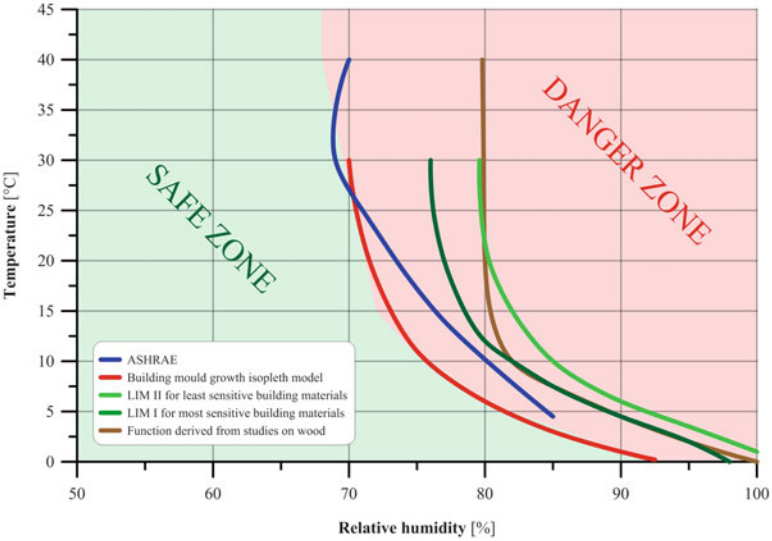

**Fig. 4.7** Temperature and relative humidity limits for mold growth including different substrates and species. *Blue Line* shows visible mold in 100–200 Days (ASHRAE), *Red Line* shows building mold growth isopleths model, WUFI-Bio LIM 0 for culture media, both *Green Lines* show the low limit for germination (most and least sensitive building materials) and the *Brown Line* shows a function derived from mold on wood studies (Taken from Strang 2013)

starting point is reducing the risk of germination. This avoids the damage due to digestion and staining. If germination occurred, a quick response in the form of desiccation is required to reduce the extent of damage. After germination, growth can take place. If this growth is minor, damage is most distinct on glossy surfaces and surfaces with high information density. Germination followed by sustained major growth would be of obvious grave concern to many collections. Finally if climatic conditions are maintained, germination and propagule dispersal increase further contamination and most importantly this will pose a respiratory hazard to human health.

Based on the literature cited by Strang (2013), some environmental guidelines for museums are provided in Table 4.2.

Molds as a group are very capable of functioning over a wide range of temperatures, with optimal growth within the temperature limits of human comfort, but at high relative humidity (70 % and up). Thus, mitigating mold risks is primarily done through dehumidification. Considering that the environment is a dynamic mold inducing system, dwell time in optimal humidity and temperature is a combination of the static exposure risk delayed by moisture absorption into the substrate at the onset of higher humidity and retained by desorption after the driving humidity declines. For sustainability discussions, acknowledging a dynamic system requires people to state 'how frequent and how deep into the dangerous region can we go, yet avoid disaster by relying on a reset towards safety in the periods we are out of danger?' (Strang 2013, p. 142).

**Table 4.2** Microbial growth limits, temperature and humidity (Strang 2013, p. 123)

| Temperature observation | | Humidity observation | |
|---|---|---|---|
| −7.5 °C<br>(18.5 °F) | Lowest limit of growth | 70 % RH | Lowest supporting microbial growth |
| −6 °C to −2 °C<br>(21 °F to 28 °F) | Slow growth of some bacteria and fungi | 75 % RH | Numerous reports of slow growth |
| 0 °C<br>(32 °F) | Slow growth of many bacteria and fungi | 80–95 % RH | "Most forms grow well" |
| 5 °C<br>(41 °F) | Few exhibit rapid growth below this temperature | 90 % RH | Some microorganism growth still inhibited |
| 15–35 °C<br>(59–95 °F) | Optimal growth and reproduction | 95 % RH | "Growth is luxurious" |
| 58 °C<br>(136 °F) | Upper limit of fungal growth | 95–100 % RH | Optimum for fungi (30 °C) |
| 65 °C<br>(149 °F) | Upper limit for actinomycetes | 100 % RH | Optimum for fungi (37.8 °C) |
| 78 °C<br>(172 °F) | Upper limit for bacterium | | |

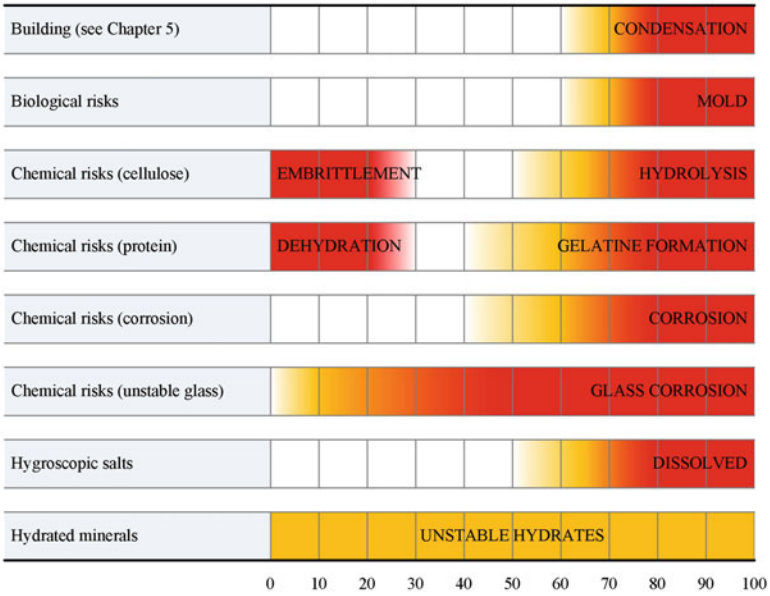

**Fig. 4.8** Risks to different types of materials as a function of the annual average relative humidity set point. *Red Color* indicates a high risk, *Orange* corresponds to some or moderate risk, and *White* indicates (very) low risk (Based on Erhardt 1994, 1996b, and Mecklenburg 2004)

Summarizing, it can be concluded that there is no single annual average relative humidity set point at which a mixed museum collection can be kept without any risk (Fig. 4.8). Exposure to relative humidities above 75 % for extended periods of time is nearly always very risky. The practical dangers of relative humidities above 75 % are the significantly faster corrosion of metals and sick glass, mold growth on organic materials, and the thriving and increased activity of a number of damaging insect species. In order to exclude the risk of mold, the relative humidity cannot remain above 75 % for a long time.

The chemical decay of cellulosic materials (by hydrolysis) speeds up as the relative humidity increases. Objects made of such materials should be kept under dry conditions in order to minimize the rate of this decay process. By doing so, the objects will release moisture and become significantly brittle, as well as more susceptible to crosslinking. As a result, the risk of mechanical damage by handling the objects increases drastically. Relative humidities below 20 % are hazardous for hygroscopic objects that are frequently used (handled) and therefore must have some flexibility.

Proteinaceous materials such as parchment undergo faster gelatinization at higher relative humidities, whereas at very low relative humidity (RH <25 %) they experience an irreversible loss of moisture (i.e. bound water) that introduces large stresses in the material. Metals also show an exponential increase in decay (corrosion) rate with increasing relative humidities above 65 %. The degree of relative humidity-related risks involving different deterioration processes for different types of materials is shown in Fig. 4.8 (Erhardt and Mecklenburg 1994).

### *4.2.4 The Relative Humidity Fluctuates Too Much for Too Long*

Hygroscopic materials will absorb or release moisture from/to the surrounding air as a result of changes in relative humidity. The question is, how hazardous these relative humidity fluctuations are for mixed collections. Absorption or release of small amounts of moisture by hygroscopic materials results in small volume changes that are generally reversible, and occur within the elastic deformation range of the material. The original shape is fully recovered when the relative humidity returns to its original value. As the relative humidity fluctuations become larger, hygroscopic materials may deform beyond their elastic range due to the absorption or release or large amounts of moisture. Deformations undergone beyond the elastic limit of the material (i.e. plastic deformations) are not reversible. If shrinkage or expansion occurs while object parts are restrained, these parts will be stretched when they shrink, and compressed when they expand. Sometimes the stress related to shrinkage and compression becomes so large that the material strength fails and deformation or fracture occurs to release the stress (Hunt and Gril 1996).

It is important to realize that fracture or deformation is not only a result of relative humidity fluctuations, the specific construction plays an essential role in the risk of mechanical damage. This is nicely illustrated by the wooden panels presented in Fig. 4.9, taken from Hoadley (2000, p. 83).

The panels have been fixed to a support in three different ways; fully restrained (left), restrained at one end (middle) and free of restrain (right). The panels are subsequently exposed to the same relative humidity fluctuation. On the right, the panels are shown after exposure to a relative humidity fluctuation starting at 40 %, going up to 80 %, and then returning to the starting point of 40 %. The third panel (from left to right) which could expand and shrink freely, retained its original form

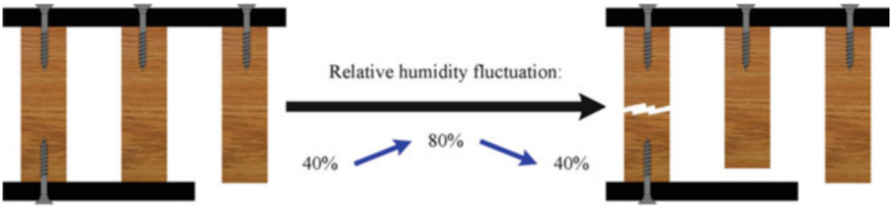

**Fig. 4.9** Wooden panels fixed in three different ways and exposed to the same large relative humidity fluctuation. Depending on the degree to which the panel is restrained from expanding and shrinking vertically, three end results can be observed: fracture, permanent shrinkage, and no change (Taken from R. B. Hoadley 2000)

after the cycle. The panel restrained on one side (in the middle) shrunk. When the relative humidity was raised, the panel's moisture content increased and it started to swell. However, because the panel was restrained and not free to expand, the wood cells were compressed against each other and permanently deformed to some extent, resulting in what is called a *compression set*. When the relative humidity was reduced to its original value, the panel shrank freely and became smaller than before. Compression set shrinkage is an often observed mechanical phenomenon on panels resulting in loss of dimension, deformation and cracks.

The first panel (on the left) was completely restrained and therefore could neither expand nor shrink due to the absorption or release of moisture. It behaved exactly the same as the one in the middle when the relative humidity was increased, becoming permanently deformed as the wood cells were compressed against each other. Upon drying, the wood released moisture and the panel started to shrink. Since it had been permanently deformed, shrinking would cause the panel to become shorter in length than originally. However, because the panel's vertical movement was fully restrained, a large amount of stress developed within the material causing it to fracture.

Similar observations on susceptible wooden structures like panel paintings and wooden panels in cabinets have led to the definition of relative humidity specifications allowing very narrow bandwidths. They still form the basis for indoor climate specifications in many museums, which have emerged from the finding that (very) large fluctuations in relative humidity may cause permanent deformation or fracture (Fig. 4.10). The question is, however, how large these fluctuations can be without causing irreversible changes.

In the 1990s, research at the Conservation Analytical Laboratory of the Smithsonian Institution (Now the Museum Conservation Institute) focused on the relationship between relative humidity fluctuations and the development of mechanical stress in clamped specimens of different materials (Mecklenburg

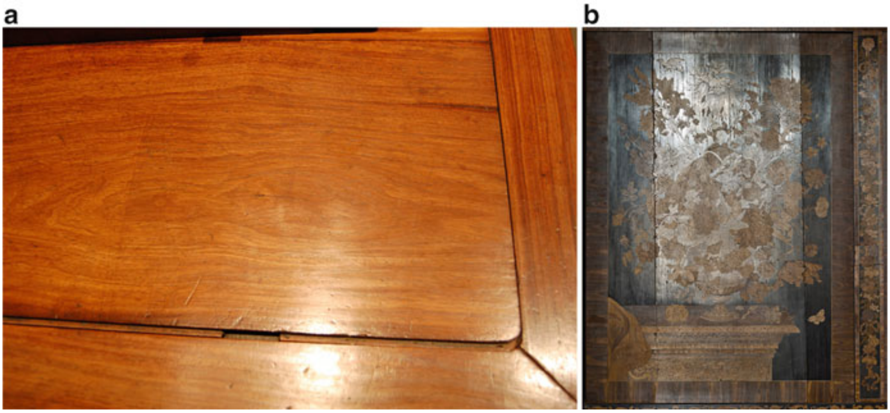

**Fig. 4.10** Two examples of permanently deformed objects. Shrunken tabletop panel with noticeable gap between the bottom panel and frame (**a**), and cracked veneered door of a cabinet, the damage indicates the construction of the panels underneath, which have shrunk (**b**)

2007; Mecklenburg and Tumosa 1991, 1999; Mecklenburg et al. 1994, 2004). Stress-strain curves for many hygroscopic materials found in museum collections were determined. The yield point of wood, ivory, and some types of artists' materials such as hide glue, pigments and binding media, have been determined using the respective stress-strain diagrams. In order to define acceptable bandwidths, i.e. the relative humidity ranges within which the risk of mechanical damage is nil, three criteria have been adopted:

1. The materials/objects in the collection are fully restrained and cannot move (expand or shrink) freely, which corresponds to the worst case scenario.
2. The restrained materials/objects are initially free of stress, which corresponds to materials that have their stresses relieved by relaxation.
3. The elongation (or compression) of the material never exceeds its yield point. In other words, the material always stays within its elastic deformation range.

Different materials generally found in museum collections will be discussed in greater detail on the following pages.

## Wooden Artifacts

The dimensional response of wood varies in different directions under the influence of loading, an applied force or a change of moisture content because of the wood's anisotropy. Its response to moisture is most pronounced tangentially (across the grain); it halves along the radial axis and is even less pronounced longitudinally.

To prevent warping of wooden panels the wood is traditionally cut in such a way that the grains are evenly distributed perpendicularly, this is called quarter sawn. Also for most panel paintings from northern Europe the wood has been cut in the radial direction (i.e. quarter sawn). The dimensional response of wood to changes in relative humidity along this direction is approximately 50 % of its response along the tangential direction (see Fig. 4.11).

The equilibrium moisture content of wood depends on the 'direction' of the relative humidity fluctuation. Equilibrium moisture content measurements carried out at different relative humidities during the drying of wood will be slightly higher than those measured at the same relative humidities during the moistening of the wood. Such a behavior is called hysteresis (not shown in Fig. 4.11). Figure 4.11 shows the equilibrium moisture content as a function of relative humidity, and the extent of shrinkage in the tangential and radial direction as a function of the equilibrium moisture content (Hoadley 2000, p. 119).

The risk of a fluctuating relative humidity for wooden artifacts can be seen as having two distinct components. On the one hand, there is the shrinkage/expansion of the artifact as a whole, which can cause stress build-up if the artifact is (or parts of it are) restrained from moving. On the other hand, it is necessary to consider the moisture gradient between the core and the surface of the artifact. The first risk applies mainly to slow relative humidity fluctuations, whereas the second becomes more relevant for (very) rapid fluctuations.

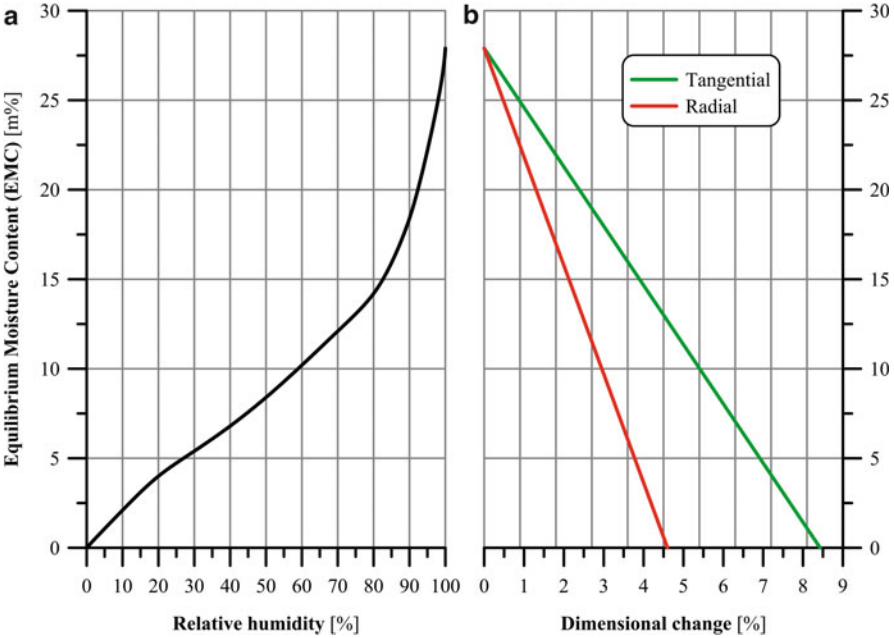

**Fig. 4.11** Equilibrium moisture content of wood (Red Oak) as a function of relative humidity (**a**). Shrinkage in the radial and tangential directions of the same type of wood at different equilibrium moisture contents (**b**) (Based on R. B. Hoadley 2000)

Measurements of the relationship between relative humidity fluctuations and the build-up of stress in clamped specimens acclimatized to 50 % relative humidity have indicated an elastic deformation range for wood between 37 and 62 % relative humidity (Mecklenburg 1994). A relative humidity fluctuation outside this range can cause permanent deformation or fracture to restrained wooden objects acclimatized to 50 % relative humidity. Research has shown that mechanical properties such as elasticity, elongation at break, and dimensional response of seventeenth century wood and fresh wood samples are virtually the same (Erhardt 1996a). When wooden artifacts are manufactured and kept in humid or dry climates, where the average relative humidity is almost always above 62 % or below 40 %, a smaller relative humidity fluctuation will cause deformation.

A classification of wooden objects into sensitivity categories for relative humidity fluctuations, based on their composition and construction, has been developed by the Canadian Conservation Institute (Michalski 1996a). A set of objects of medium sensitivity were used as a reference to define the different sensitivity categories. The wood absorption coefficient at low relative humidities (0–10 %) is approximately two times larger than at a relative humidity between 40 and 50 %, and this value triples above 85 % relative humidity. As a result, fluctuations of ± 20 % around a reference value of about 50 % relative humidity result in less than half as large dimensional changes than those caused by fluctuations of ± 40 % around that same value (Michalski 1993).

Some objects are very susceptible to fracture due to the presence of a brittle surface layer, whereas other objects are less sensitive because its parts (panels, etc.) are free to shrink and expand. Table 4.3 below can help inform the choice of relative humidity conditions under which to place different types of wooden objects.

The risks of damage to the different sensitivity categories should always be considered in the light of two other aspects: the response time, and the degree of (stress) relaxation. The response time of objects is addressed later in this chapter. For relaxation, it may be noted that wood slowly releases stress when under constant strain. Depending on size, density and age this process takes a month to several months, and it allows the wood to equilibrate at a much lower stress level. Effectively, the wood becomes much less stiff if a load is applied over a sufficient time period. Consequently, the strain at failure is considerably extended: an increase of this parameter from 0.2 to 0.7 % was observed for fir specimens loaded in tension (perpendicular to the grain direction) over 1 month when compared to a rapid loading under just an hour (Madsen 1975, 1992). As a result, slow fluctuations, like seasonal adjustments, form a significantly smaller risk than fluctuations that happen within a time frame that is shorter than the response time and the relaxation time (typically 1 month).

Similarly, hourly relative humidity fluctuations will produce a strain difference between the core and the surface of the wooden artifacts, resulting in stress. The stress will be higher than fluctuations with the same amplitude that occur in, for example, 24 h (Kozłowski 2007). The risk of surface damage to hygroscopic objects is therefore smaller when the fluctuation is slower, for example when the surrounding air is slowly heated instead of fast. Since heating for short time frames (especially in churches) is actually done only for human comfort purposes, the use of localized heating close to the user is a good alternative (Camuffo and Valle 2007) that reduces the risk of dry environments near objects.

Panel paintings form a group of objects that deserve special attention among wooden artifacts in a museum collection, since they have a complex laminate structure consisting of several layers. For their manufacture, the wooden support is first pretreated with animal or hide glue, onto which a textile layer is sometimes placed. The panel then receives multiple coats of gesso (mixture of hide glue and chalk or gypsum) and, after drying, the paint layers and/or gilding are applied. Roughly speaking, different damage processes affecting panel paintings due to relative humidity fluctuations can be distinguished (Fig. 4.12): fracture of the wooden support, plastic deformation of the wooden support, and the occurrence of craquelure in the paint layer.

Deformation results from the expansion or shrinkage of one side of the wooden panel. Its front side is covered by a laminate of paint and gesso layers that function as a moisture barrier, whereas the reverse side is sometimes left untreated (i.e. without any type of coating). In such cases, relative humidity fluctuations will cause moisture transport through the reverse side of the panel. By releasing moisture during a dry period, the reverse side will shrink more than the front side,

**Table 4.3** Sensitivity categories of wooden artifacts for relative humidity fluctuations, including expected effects of exposure to fluctuations around an average reference value of relative humidity = 50 % (Michalski 1996)

| Vulnerability | Artifacts examples |
|---|---|
| Very high<br>±5 % relative humidity Gradual fatigue fracture<br>±10 % relative humidity Fracture possible each cycle<br>±20 % relative humidity Fracture definite first cycle<br>Much of this type of fracture has already occurred in old artifacts. Only artifacts from less fluctuating or higher annual average conditions, or those recently re-attached by inflexible treatments, will fall in this category | This class of wooden artifact breaks the rules of cautious woodworking, or else the fracture of these coatings has never been considered disfiguring<br>– Aged glue, lacquer, varnish, gesso, or oil paint that bridges joints where wood grains meet at right angles (lap joints, mortise and tenon joints, etc.; also, any knots in wood components)<br>– Aged glue, lacquer, varnish, gesso, or oil paint that bridges a crack formed by a check, knot, side-by-side butt joint, or mitre joint<br>– Inlays of metal, horn, ivory, or shell (but not wood; marquetry is considered below as medium vulnerability, since it is much tougher and more resilient)<br>– The longer the inlay runs across the grain, the more vulnerable the piece |
| High<br>±5 % relative humidity No fatigue fracture<br>±10 % relative humidity Gradual fatigue fracture, or permanent deformation<br>±20 % relative humidity Fracture possible in each cycle<br>±40 % relative humidity Fracture definite first cycle<br>Much of this type of fracture has already occurred in old artifacts. Only artifacts from less fluctuating or higher annual average conditions, or those recently re-attached by inflexible treatments, will fall in this category | – Veneer over corner joints where wood grains meet at right angles (lap joints, mortise and tenon joints, etc.; also, any knots in wood base components)<br>– Lacquer, oil paints, or gilding over single knot-free wood components, or over joints that use feathered inserts, fabric, tissue, etc. that are still sound. When new and fairly flexible, these layers may drop to only medium vulnerability<br>– Fretwork, applied ornaments (especially if the wood grain follows the notch), and assemblies with metal bands, bolts, nails, or screws that restrain the wood unevenly<br>– Checked timber or sculpture with a hard new fill; cracked panel or panel painting in a rebate or cradle that jams<br>– Large pieces of recently seasoned wood such as folk art, also all knots and uneven grain in wood must be considered prestressed in this way<br>– New plywood, newly steam-formed wood held by other components<br>– Panels near intermittently damp walls, floorboards over damp crawlspace<br>– Glued veneer or joints where the glue bond has softened and readhered at the expanded component position |

(continued)

**Table 4.3** (continued)

| Vulnerability | Artifacts examples |
|---|---|
| Medium<br><br>±10 % relative humidity No fatigue fracture<br>±20 % relative humidity Gradual fatigue fracture, or permanent deformation<br>±40 % relative humidity Fracture possible in each cycle | – Most wood joinery, veneers, and marquetry over single, clear pieces of wood at crossed grain<br>– Any pre-stressed pieces from above that have stress-relaxed for more than a decade<br>– Any wood with little or no coating, subjected to a relative humidity fluctuation shorter than its response time. This leads to warping or surface checking, e.g. backs of picture frames; on exposed end grain it results in end-checks, e.g. tenons, dovetails, feet of furniture, overhangs in carved totem poles |
| Low<br>(given either a slow enough change in relative humidity or a good moisture barrier coating)<br><br>±40 % relative humidity Possible accumulation of fatigue fracture or plastic deformation if the freedom to move, or the coatings, or the slowness of the fluctuation are less than perfect | – Already cracked varnish<br>– Already loose joinery<br>– Floating panels<br>– Loose tabletops<br>– Tongue-and-groove or lapped planking nailed or bolted at one point only, e.g. wainscoting (unless jammed due to painting or warping)<br>– Hollowed-out sculptures, totem poles, etc.<br>– Most single-component tool handles<br>– Veneer on wood with parallel grain<br>– Joined wood components with parallel grain |

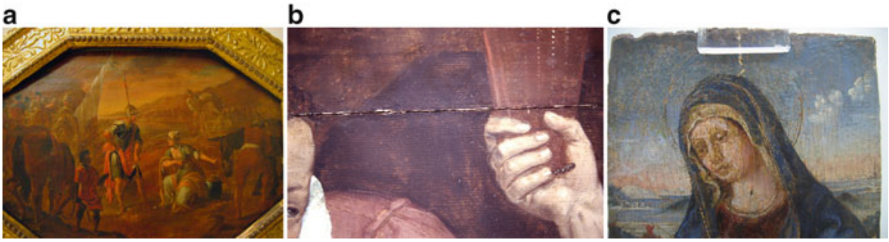

**Fig. 4.12** Climate-related damage to panel paintings: deformation (**a**); fracture of the wooden support (**b**); and craquelure (**c**)

especially since drying occurs faster than moisture uptake. This will lead to the development of a strain gradient (stress) across the thickness of the panel and, as a result, bending. Australian Aboriginal bark paintings are an example of artifacts in which this process happens very fast. In a study involving a large number of bark paintings with average dimensions of 600 × 400 × 5 mm, out-of-plane deformations of up to 24 mm have been measured during an increase in relative humidity from 35 % to 63 %. These deformations were coupled with an expansion in the tangential direction of the order of 16.5 mm (Smith and Roth 2002).

Fracture of the wooden support of panel paintings often results from a very damp period followed by a (very) dry one, comparable to the situation outlined in Fig. 4.9. It involves large relative humidity fluctuations and the resulting build-up of a large amount of stress within the material. Figure 4.12b shows fracture of a panel painting caused by failure of the humidification system during a cold winter night. The cold outdoor air admitted into the building continued to be heated, but no longer humidified. For 2 days, the malfunctioning climate control installation delivered very dry air into the exhibition room of the museum. Analysis of the outdoor temperature in that period allows an estimate of the relative humidity in the room. Assuming the most favorable conditions, a conservative estimate indicates that the relative humidity remained at 11 % continually for 2 days. Five out of seven panel paintings were split. The two panels that did not suffer any damage were hanging on a cold external wall, whereas the five damaged panels hung on a relatively warm inner wall. Because of the low temperature of the external wall, the local relative humidity was higher thus preventing the two panels from being split. It's worth noting that for this damage to occur, not just the size of the fluctuation is relevant but also the duration. Dropping to 11 % relative humidity for 30 min would probably have done little damage in comparison to this level for 2 days.

The risks of mechanical damage to panel paintings was studied by investigating the mechanical properties of individual layers found on paintings: glue, ground, oil paint. The one layer undergoing the most pronounced dimensional changes during relative humidity fluctuations can be considered as the most important in determining the risk of fracture. In early panel paintings, the gesso layer is the weakest link. The response and the mechanical properties of gesso depend primarily on the type and amount of animal glue in the mixture. The typical crack pattern found in panel paintings can be explained by the difference of response of the gesso layer and the wooden support (Michalski 1991). Whenever the panel painting is exposed to a high relative humidity (including during its manufacture), the gesso layer becomes soft and relaxed. When the relative humidity decreases to about 50 %, the gesso layer releases moisture but cannot shrink freely.

The wood is anisotropic (the swelling/shrinkage depends on the grain direction) and the gesso is isotropic (no preference into the properties). So when the wood wants to shrink in the radial direction, the gesso will also shrink. So in the radial direction the stress induced only depends on the difference in strain between wood and gesso. In the longitude direction, the wood shrinkage is very small compared to the shrinkage of the gesso. The strain difference will be larger than in the radial direction and stress will be induced (Aurand 2014). If the yield point is exceeded, cracks will be formed. These cracks, which run across the grain, especially on the more dense wood, are referred to as primary cracks (see Fig. 4.13).

The presence of cracks in the gesso layer of panel paintings indicates that the artifact has been exposed to relative humidity fluctuations reaching values larger than 70 % and lower than 20 %. If the gesso is (pre)conditioned at 50 % relative humidity, the calculated yield point is reached at about 28 % relative humidity upon drying, and at about 66 % upon increasing the relative humidity for wood in

**Fig. 4.13** A panel painting showing significant cracking and loss of paint. The areas were paint has been lost completely, clearly shows the underlying wood structure. The color of the wood is a good indicator when paint was lost; Relatively dark wood indicates loss happened a while ago, while the bright colored wood shows that the loss of paint is recent and loss should be considered an active process

tangential direction (Mecklenburg 1994). It should be noted that this calculation is based on a very flat swelling isotherm for wood in the mid-range of the relative humidity. Based on measurements of many woods the isotherms are presumably much steeper than the one used by Mecklenburg, which reduces the allowable relative humidity range.

### Canvas Paintings

Paintings on canvas also represent a complex group of artifacts in museum collections. Many different types of materials are and were used to produce canvas paintings. Its manufacture also involves the superimposing of different layers with potentially different responses to relative humidity fluctuations. Traditional Western paintings are generally composed of a woven linen canvas that has been stretched and sized with animal glue, onto which the ground and paint layers were then applied (Fig. 4.14).

In order to estimate the risk of paint cracking it is necessary to know the extent to which the different layers of the painting undergo dimensional changes in response to relative humidity fluctuations, and where, between the layers the weakest link is located. The risk of cracking is partly determined by the degree of pigmentation of the binding media and the age of the painting, i.e. the brittleness of the image layer.

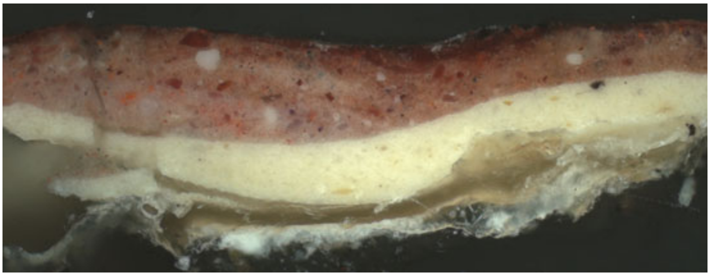

**Fig. 4.14** The different layers of an oil painting on canvas. From *bottom* to *top*: sizing, white ground, oil paint with red and white pigments and varnish (Photo: Geldof, Cultural Heritage Agency of the Netherlands)

**Fig. 4.15** Detail of surface cracks in an oil painting exposed to a large relative humidity fluctuation. Starting condition of 90 % RH (**a**); dried to 4 % RH (**b**); and returned to 90 % RH (**c**) (Source: V. Schaible 1990)

Moisture ab- or desorption by canvas paintings generates stress between the support (the linen canvas) and the paint layers. These layers do not shrink or expand to the same extent as the textile support does, resulting in the build-up of stress with an accompanying risk of fracture (Mecklenburg 1991). Whilst the individual fibers of a stretched canvas exposed to an increasing relative humidity will expand, the twist of the thread will increase and therefore the textile as a whole shrinks, which is counteracted by the stretcher. This results in stress within the artifact. The question is how large these stresses can be before cracks in the paint are formed, or which stresses (i.e. relative humidity fluctuations) cause paint cracking?

The movement of an extensively cracked oil paint exposed successively to extremely dry (relative humidity = 4 %) and extremely damp (relative humidity = 90 %) conditions has been shown in the film '*Vom Atmen der Bilder*' by Volker Schaible (1990a). Some frames of the film are shown in Fig. 4.15, where it can be clearly seen how the edges of the paint flakes buckle. After a large number of such relative humidity cycles, the occurrence of paint loss is possible. It is also clear, however, that despite the extreme relative humidity fluctuation between 4 and 90 %, the paint (flake) does not detach itself from the support after only a few cycles. This shows how robust or rather how flexible paintings can also be.

Research has also been carried out into the mechanical properties of the individual layers traditionally found in paintings: support (canvas), sizing, ground, and oil paint (Mecklenburg 1991). Hide glue is the strongest and stiffest of all materials in a painting, and it shows a large response at low relative humidities. Hide glue becomes very elastic above 80 % but loses its strength, while simultaneously the canvas shrinks significantly. Stresses are developed that will cause the glue to detach from the support causing paint loss. Such a risk is particularly relevant for paintings placed against (very) cold walls, where due to thermal shielding the relative humidity can be very high locally between the canvas and the wall. The sensitivity of hide glue and oil paint to relative humidity fluctuations can be separately assessed by looking at the condition of oil paint on other types of support. Oil paintings on copper are generally found in exceptionally good condition (Horovitz 1999). Assuming that these objects have experienced similar climatic conditions in the past, it can be stated that the elasticity of oil paint by itself is considerable.

A disadvantage of studying the mechanical properties of individual layers is that the behavior of the assembly of layers as a whole is not evaluated. There is relatively little research done on the climatic impact on layered systems. Investigation into the response of a 1924 painting has shown that the wooden support and the paint were in good condition, except for an area where the maker glued a layer of paper over a knot in the wood. In this area, the paint experienced extensive cracking and loss. The paper turned out to be too flexible to adequately support the aging paint. Although the paint layer sitting over the paper had exactly the same composition and age, and had been exposed to the same environmental conditions as the rest of the painting, it has locally cracked and delaminated (Berger and Russell 1994).

In the nineteenth century, glue-paste lining was carried out as a preventive measure to stop possible deterioration of still-sound canvases by making them stiffer and less hygroscopic. In the mid-nineteenth century wax-resin lining was developed to make the canvasses less hygroscopic. In those days many canvas paintings, like the ‘Nightwatch’ made by Rembrandt, were treated with a wax-resin mixture. The mixture was melted at elevated temperatures and applied to the back of the painting. The canvas and part of the paint layer became impregnated with this water-repellent mixture. This treatment significantly decreases the moisture absorption of the painting and make them almost insensitive to any relative humidity fluctuation (Hedley 1988). In the years between 1975 and 1984, there was a rapid growth in lining technology, and synthetic adhesives such as BEVA 371 became more popular. However, these glue-paste and BEVA linings are more susceptible to changes in relative humidity (Young and Ackroyd 2001).

Stress built up in a rectangular painting, partly caused by re-stretching, results in a characteristic pattern of cracks diagonally oriented across the corners of the painting (see Fig. 4.16).

Another frequently occurring crack pattern in canvas paintings is known as the ‘stretcher effect’. In the areas where the wooden stretcher is underneath the canvas there are hardly any cracks, whereas elsewhere in the canvas clearly recognizable patterns can be observed. Such an effect is particularly common in paintings that

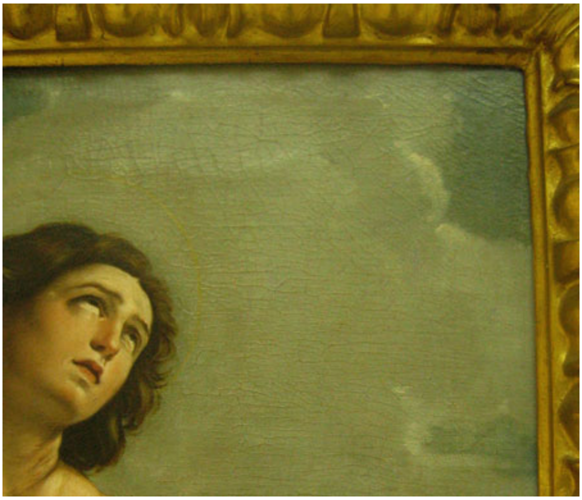

**Fig. 4.16** Crack pattern in an oil painting caused by relative humidity fluctuations

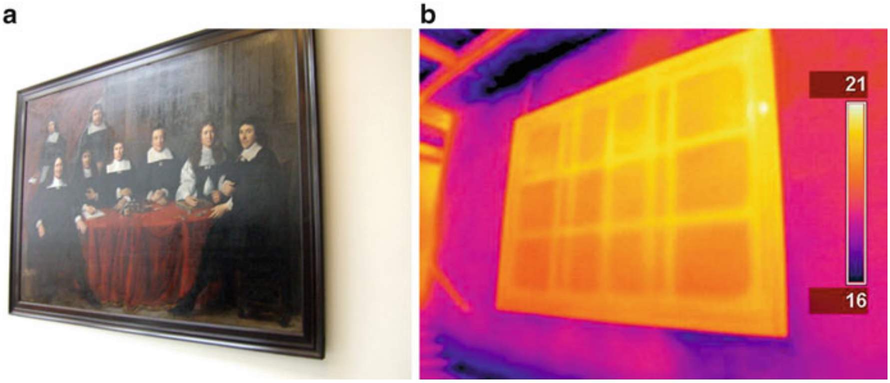

**Fig. 4.17** A canvas painting against a relatively cold wall (**a**); and the temperature profile of the same painting clearly showing the stretcher (**b**) (Photos: Martens, Eindhoven University of Technology)

have hung on cold walls for a long time. It was initially attributed to the moisture buffering capacity of the stretcher. Recent research has shown, however, that the local buffering effect of the stretcher is negligible compared to its thermal insulation effect. In other words, the canvas is locally isolated from the underlying cold wall by the stretcher (Ligterink and DiPietro 2007). Therefore the unshielded canvas will experience many temperature cycles, with related humidity fluctuations, whereas the shielded part of the canvas will be exposed to less fluctuations. This thermal effect can clearly be seen in the false-color infrared image shown in Fig. 4.17, where the areas of the canvas over the stretcher (yellow) have a higher temperature than the remaining ‘unprotected’ areas (darker yellow/orange). The temperature of the wall is approximately 17 °C (63 °F). The 'unprotected' areas of the canvas have a temperature of about 19 °C (66 °F), whereas in the areas insulated by the stretcher the temperature of the canvas approaches that of the room, i.e. 21 °C (70 °F).

Estimating the risks of relative humidity fluctuations to paintings is not straightforward. There are different materials and geometries that, in addition to the current condition of the painting, influence the way these artifacts respond to fluctuations. A general, rough risk estimate for the different climate classes would be (ASHRAE 2011):

AA. No risk of mechanical damage to most paintings;
A. Small risk of mechanical damage for highly vulnerable objects. No risk of mechanical damage for most paintings;
B. Moderate risk of mechanical damage for highly vulnerable objects. Tiny risk of damage to most paintings;
C. High risk of mechanical damage for highly vulnerable objects. Moderate risk of damage to most paintings;
D. High risk of sudden or cumulative mechanical damage to most paintings.

Details about the relative humidity conditions for the different climate classes can be found in Table 4.9 and in appendix 7.

## Ivory and Objects Made of Bone

Ivory is the hard, white material that constitutes the bulk of the teeth and tusks of animals such as the elephant, hippopotamus, mammoth, walrus, and narwhal (Fig. 4.18). Compared to wood, ivory is somewhat less responsive to relative humidity

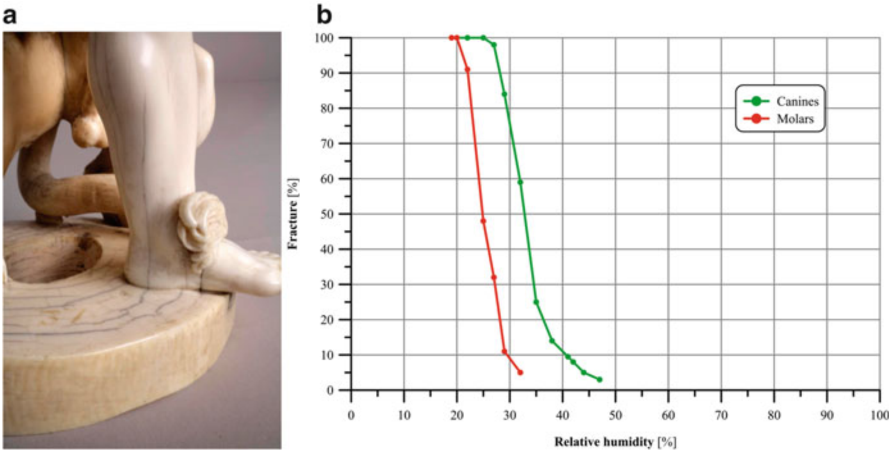

**Fig. 4.18** Detail of an ivory statuette (Simson and de Leeuw, Leonhard Kern, 1588–1622) with characteristic fracture lines (**a**) (Photo: Jehle, Staatliche Museen zu Berlin). Cumulative fraction of fractured teeth upon exposure to increasingly drier conditions (**b**) (Based on S. L. Williams 1991)

fluctuations. Research has shown that the unrestrained swelling and shrinkage of walrus tusks pre-conditioned at 48 % relative humidity still happen within the elastic deformation range of the material for relative humidity fluctuations ranging between 27 and 68 % (Mecklenburg 1999). By exposing teeth to increasingly drier conditions a fracture threshold can be observed (Fig. 4.18). This threshold differs for different types of teeth: around 38 % relative humidity for canines, and 27 % for molars (Williams 1991). Which corresponds well with the thresholds found by Mecklenburg.

A relative humidity of 50 % ± 10 % is considered safe for ivory artifacts. Restrained ivory parts, such as inlays, belong to the 'very high vulnerability' category, for which a narrow relative humidity range of ± 5 % must be maintained (see Table 4.3). The risk of mechanical damage to ivory by high temperature is considered low, up to a temperature of 30 °C (86 °F) (Lafontaine and Wood 1982).

### Textiles

The term textile encompasses a multiplicity of materials and constructions: from synthetic to natural fibers, loosely or very tightly woven, stretched or not. Generally it can be said that hygroscopic objects under stress face a higher risk of damage than non-woven fibers with low equilibrium moisture content, such as many synthetic fibers.

Many textile artifacts are made of fibers twisted into threads, which are then further processed into fabrics. By absorbing moisture from the surrounding air, the individual textile fibers swell (more in diameter than in length). As a result, the twist of the thread gets tighter and shrinks in length, and the fabric contracts (Boersma et al. 2007). This swelling shrinkage behavior of textiles seems to be the opposite of how other hygroscopic materials such as wood react to changes in relative humidity. Fabrics shrink when the relative humidity increases and expand at lower relative humidity. The rubbing of fibers and threads against each other is generally considered a big risk. Luxford (2009) concluded "Year long accelerated ageing experiments < on undyed samples > have demonstrated that although the inclusion of UV radiation during light ageing increased the rate of deterioration, light ageing caused small changes to silk. Thermal ageing with different humidity levels demonstrated increasing the relative humidity (RH), increased the rate of silk deterioration significantly." To increase the lifetime of silk on open display in historic houses the relative humidity should be kept below 50 % (to a minimum of 30 % RH) and at lower temperatures with the exclusion of UV radiation. Environmental monitoring behind tapestries showed microclimates with high relative humidities. Since this will increase the rate of silk deterioration, mitigation of these microclimates would increase the lifetimes of silk tapestries significantly.

**Table 4.4** Climate specifications for long term storage of archival collections according to regulation 13 Article 54a (December 2009)

| Collection | Temperature | Relative humidity |
|---|---|---|
| Paper, parchment, wax, leather, textile, wood, photographs on paper and optical discs | 18 °C −2/+1 °C<br>(64 °F −4/+2 °F) | 50 % ± 5 % |
| Black-and-white negatives | 13 °C ± 2 °C<br>(55 °F ± 4 °F) | 35 % ± 5 % |
| Black-and-white di and tri acetate negatives, nitrate negatives and color negatives | −20 °C ± 2 °C<br>(−4 °F ± 4 °F) | 38 % ± 5 % |
| Mother copies of tapes | 10 °C ± 2 °C<br>(50 °F ± 4 °F) | 40 % ± 2 % |
| Work copies of tapes | 18 °C ± 2 °C<br>(64 °F ± 4 °F) | 40 % ± 2 % |

Similarly dyed natural fibers can experience a somewhat faster discoloration by light at higher relative humidities (Kühn 1967). But again, the impact of the climate can be neglected when compared to the effect of light on many types of dye.

Another aspect is that, for free-hanging objects of large dimensions, like tapestries, there can be a significant increase in weight as a result of moisture absorption. This gravitational force, combined with weakened threads, can lead to rupture. Especially of the weft, which is significantly weaker than the warp. Proper support of these types of objects is therefore necessary. At low relative humidities the fabrics release moisture and swell. Stretched fabrics will sag. If the fabric has been treated with animal glue, it will dry out and become brittle. Stretched textiles exhibit only a moderate variation in tension between 0 and 75 % relative humidity. However, as the relative humidity increases between 75 and 100 %, they shrink enormously (Michalski 1993).

## Library and Archival Collections

Archival collections are typically under strict regulations concerning the specifications for buildings and storage spaces where they are kept. In the Netherlands a distinction is made between archival facilities for short term storage (up to 20 years), and those for permanent storage. The documents in permanent storage must be accessible and kept ‘forever’. So the aim of the archival collection manager is to have no deterioration of the collection at all. Therefore climate specifications, in the Dutch National Archives, specify that the maximum allowable relative humidity fluctuation for the long term storage of these collections is 5 % (National Archief 2008). The climate specifications for archival collections, as published in article 32 of the Dutch Regulation for archival building and facilities, are shown below in Table 4.4.

Elsewhere in the world similar climate specifications can be found. For example, in the UK the BS5454 was in force until 2012, in which a storage temperature

**Table 4.5** Estimated mechanical risks for archival materials resulting from relative humidity and temperature fluctuations (±% relative humidity, ±°C), after Michalski (2000)

| T and relative humidity fluctuation | Very sensitive documents | Sensitive documents | Low sensitivity documents |
|---|---|---|---|
| ±5 | None to tiny damage | No damage | No damage |
| ±10 | None to small damage | None to tiny damage | No damage |
| ±20[a] | Small to significant damage | None to small damage | None to tiny damage |
| ±40 | Severe damage | Small to significant damage | None to small damage |
| | Layered structures (laminates) containing image/data layers, with poor strength and moderate to high differences in expansion | Layered structures (laminates) containing image/data layers, with medium strength and moderate to high differences in expansion | Support layer containing finely dispersed image/data layers, with medium strength and moderate to high differences in expansion. Laminates with low differences in expansions |
| | Thick images on parchment | Most photographs, negatives, and film | |
| | Globes | Most magnetic records | |
| | Thick oil-resin images on paper or cloth | Most oil paintings | Most single sheets of paper with print, halftones, line drawings, inks, washes |
| | Documents listed as medium sensitivity that have weakened substantially due to UV exposure or other chemical deterioration processes | Thin, well adhered inks on parchment | |
| | | Gouache on paper | Most books |
| | | Book bindings of vellum and/or wood | Most CD's |

[a] Temperature not above 30 °C (86 °F), relative humidity not above 75 %. Temperatures above 30 °C (86 °F) and relative humidities above 75 % represent a high mechanical risk for many documents due to permanent deformation and the release of stress built in during their manufacture

and relative humidity conditions for archival collections were specified as: 16 °C–19 °C ± 1 °C (61 °F –66 °F ± 2 °F), and 40 %–65 % ± 5 % respectively (British Standard Institution 2000). In 2012 PAS198 was published (British Standard Institution 2012). Contrary to the BS5454, PAS198 is a risk based guideline. It focusses on the four major agents of deterioration: temperature, relative humidity, pollution and light and leaves space to find the optimum climate conditions for one's own collection. Also mitigation measures for the deterioration effects on the materials commonly found in collections is provided.

Contrary to the standard in the Netherlands, the Canadian Conservation Institute (CCI) published a bulletin with recommendations for climate conditions in archives and libraries (see Table 4.5), based on the risks to the collection from incorrect indoor climate (Michalski 2000).

## 4.3 The Proofed Relative Humidity Fluctuation

In conservation practice, the current state of a collection is used in many cases as an indicator of the risks to the collection. Cracks, fractures, and paint losses are considered direct evidence of a poor indoor climate, and decisions to improve the environmental conditions are often made based on these observations. The fact that the current state of an object is a result of all environmental action it has been exposed to since the moment of its production, or since it has last been given conservation treatment, is often not taken into account. A cabinet belonging to the collection of the (Danish) National Museum in Copenhagen is shown in Fig. 4.19. It can clearly be seen that, the damage observed in the cabinet in 2008 was already present in 1980, and that this damage occurred to a large extent before the piece was acquired for the collection in 1945. In the last decade, the cabinet was exhibited in a former palace, now a museum, at a relative humidity that fluctuated from 20 % in the winter to about 58 % in the summer. Between 1999 and 2006, the average relative humidity in that location was 39 %, ranging from a maximum of 61 % and a minimum of 17 %. By disregarding the outliers in the climate data, and using only the data points between the 8th and the 92nd percentiles, the cabinet has experienced relative humidity values between 28 and 50 %. Despite this long period of exposure to such fluctuating indoor climate conditions, the cracks in the cabinet wooden panels have not grown bigger. It is unclear when this damage was formed in the past. It probably results from the introduction of heating in the past and a sudden shift to very warm and dry environments in winter leading to permanent shrinkage of the panels.

A relatively simple estimate of the risk of mechanical damage to a collection can be made based on the so-called 'proofed relative humidity fluctuation' (Michalski 1993, 1996). Future relative humidity fluctuations do not constitute a significant risk of fracture or detachment of layers (delamination) if these fluctuations are expected to be smaller and around the same central value as the relative humidity fluctuations the object has already been exposed to in the past.

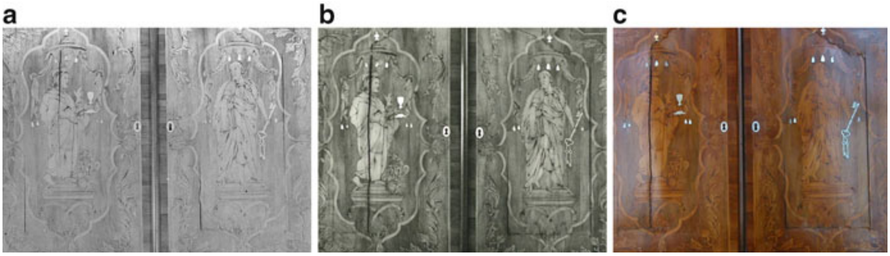

**Fig. 4.19** Veneered cabinet doors during permanent exhibition in 2008 (**c**), whose cracks were all already present in 1980 (**b**), and had occurred to a large extent when the cabinet was acquired for the collection in 1945 (**a**) (Photos: 1945: The National Museum of Denmark, 1980: Ryhl-Svendsen)

A 2 year research project on the crack propagation of an eighteenth century cabinet in the National Museum in Krakow, using acoustic emission, showed that although the relative humidity dropped from 50 % in summer to about 35 % in winter, damage formation was insignificant (Łukomski 2013). The analysis of the data accumulated over a period of 2 years allowed the risk of damage to be quantified, expressed in terms of crack propagation, as a function of the magnitude of the RH falls of the duration compatible with the response time of the object. Thus, the total area fractured was 12.1 $mm^2$ corresponding to 1.2 mm of crack propagation in the two 10-mm-thick panels monitored, or 0.6 mm per year on average (Strojecki et al. 2014).

It should be noted that the proofed fluctuation deals with cracking after one cycle. Obviously a large amount of cycles that are just below the proofed fluctuation might also lead to mechanical degradation. This process is called fatigue fracture from compression set, i.e. fatigue of the cell walls. Fatigue fracture is a result of multiple shrinkage/expansion (strain) cycles. The performance of materials in high-cycle fatigue situations can be characterized by the so-called S-N curves, where the magnitude of a cyclic stress is plotted against the number of cycles to failure. These curves have an S shape, starting with the strain at which fracture occurs after only one cycle, and leveling off to a plateau indicating that cyclic strain can continue more or less indefinitely without causing failure (fatigue threshold) (Michalski 1991). So while the proofed fluctuations takes the largest single fluctuation that can be experienced without fracture, fatigue is due to a number of cycles of a certain relative humidity fluctuation. Generally (although there isn't a lot of fatigue research on collections) the safe value for a single fluctuation is significantly larger than the fatigue value, which seems to be reducing the safe size of fluctuations. This complicates somewhat the concept of proofed fluctuation, since fatigue adds a range of values less than the proofed fluctuation which may lead to fracture if repeated sufficiently. It is therefore more precise to consider a pattern of previous fluctuations – a proofed frequency distribution of fluctuations – instead of a single value (Michalski 2007).

The S-N curve determined experimentally for a gesso layer on a wood support started at a strain of approximately 0.004 for fracture in a single cycle and dropped to a plateau of 0.002 where cyclic strain was tolerated for up to 36,500 cycles, corresponding to 100 years of diurnal strain cycles (Bratasz et al. 2011). Thus, the strain tolerable at the maximum number of cycles analyzed was approximately 1/2 of the single cycle fracture strain. The critical strain values of 0.004 and 0.002 can be translated into the critical amplitudes of relative humidity variations of ±12 % relative humidity and ±6 % relative humidity, respectively, when moisture expansion coefficients of the gesso, and the wood in the most responsive tangential direction are used, under an assumption that the relative humidity variations last much longer than the response time of a panel, i.e. the panel can fully respond to an relative humidity variation. Łukomski (2012, 2014) found that with increasing lime wood panel thickness the allowable relative humidity decreases, from a 2 mm thickness with an allowable relative humidity fluctuation of 15 %, to a 40 mm panel with an allowable relative humidity fluctuation of 13 %.

An estimate of the risk of fracture or delamination for an object or collection is therefore not solely based on materials science, but equally on its indoor climate history. This means that historic climate data are essential to identify and analyze the risk of mechanical damage by relative humidity fluctuations. When defining future indoor climate specifications there is no benefit in making the climate (relative humidity fluctuations) more favorable than what the collection has been exposed to in the previous years, when the collection remains the same. It must be noted that the proofed relative humidity fluctuation of a collection or a specific object can be undone by conservation treatments.

Using the concept of proofed relative humidity fluctuation it is possible to specify future indoor climate conditions by analyzing the historic climate. This is done by calculating the median (50th percentile) and the standard deviation of the relative humidity data set. The (maximum) acceptable future fluctuation is defined as the standard deviation of all historic relative humidity data (Camuffo et al. 2004; Bratasz et al. 2007; CEN 2010).

This parameter corresponds to a conservative or cautious bandwidth for acceptable relative humidity fluctuations, whose peak values are not the same as the ultimate upper or lower limits of the historic climate data set. By doing so, one compensates for the 8 % overshoot and undershoot of the specified bandwidths that is normally accepted by climate consultants and engineers.

## 4.4 The Response Time of Hygroscopic Materials

In addition to understanding the sensitivity of objects to relative humidity fluctuations, it is also necessary to know how fast the objects react to such fluctuations in order to estimate the risk. In general, short duration disturbances in relative humidity do not cause significant changes in the equilibrium moisture content of most hygroscopic materials. Only a few objects will react noticeably to relative humidity fluctuations of the order of 1 h. Fifteen minute fluctuations resulting from air admission by a climate control installation, therefore, do not constitute a risk to the collection – unless the relative humidity variation is large enough to cause condensation. Objects with a short response time such as a sheet of paper are often displayed behind glass, or packed in separate boxes or folders, which significantly increases their response time (Fig. 4.20). For many objects it takes days before they are in full equilibrium with the new relative humidity.

The time required for an object to reach complete equilibrium with new environmental conditions is called response time. The concept of time to reach half of the full response, i.e. ‘half-life’ is often used in the (technical) literature to characterize this type of behavior. The ‘half-life’ is the time it takes for the object to undergo half of the complete change. Since the variation of an object’s moisture content in response to changing relative humidity conditions is more pronounced in the beginning of the equilibration process, the ‘half-life’ reflects this faster, first half of the object’s response. If an object is exposed to a relative humidity fluctuation

**Fig. 4.20** Four different situations showing hygroscopic materials with different response times: a bible on open display with a very short response time (**a**); paper objects displayed behind glass in a print room with a moderate response time (**b**); objects stored in cardboard boxes with a long response time (**c**) and a panel painting in an airtight microclimate box with a very long response time (**d**)

and the equilibrium moisture content will, for example, decrease by 5 %. This moisture change will follow an exponential decay curve with a plateau. So the time required for the first 2.5 % change will be the same as the time needed for half of the next 2.5 %, i.e. 1.25 %, moisture content change. Subsequently half of the next 1.25 % (0.625 %) will again take place in the same amount of time: the half-life. So, an object requires approximately three times its ‘half-life’ to reach more or less complete equilibrium.

The relative humidity equilibration ‘half-life’ depends on the type of material, the geometry of the object, and its surface finish. Large, thick wooden panels with a moisture barrier on the surface will equilibrate much slower to a new environment than a small, thin, and untreated wooden object. The rate at which panel paintings equilibrate to new relative humidity conditions, for instance, depends significantly on their finish. An unvarnished tempera painting will absorb/release moisture much faster than a gilded and lacquered surface (Allegretti and Raffaelli 2008). Cabinets displayed with their doors open will absorb and release moisture much faster than a closed piece

**Table 4.6** Time scales for different types of objects to equilibrate to changes in relative humidity. The time to full equilibration is considered as three times the object's 'half-life'

| | Type of object | Half-life ($t_{1/2}$) | Reference |
|---|---|---|---|
| Minutes | Single sheet of paper or photograph | Minutes | Michalski (1993) |
| | Bark paintings | Minutes | Tworek-Matuszkiewicz (2007) |
| | Linen and size | Minutes – hours | Michalski (1991) |
| Hours | 3-mm thick unfinished wooden plank | ±2 h | ASHRAE (2011) |
| | Ivory statuette of 100 g ($t_{1/2} = 2.79w + 4.4$; w: weight in grams) | ±5 h | Lafontaine (1982) |
| | Open book | Hours – 1 day | Michalski (1993) |
| | Oil paint and oil ground | Hours – days | Michalski (1991) |
| Days | 1-cm thick unfinished wooden plank | ±1 day | ASHRAE (2011) |
| | Wooden cabinet with open doors | ±2 days | ASHRAE (2011) |
| | Single sheet of paper or photo inside a cardboard box | 2–3 days | Bigourdan et al. (1997) |
| | Wooden frame (stretcher) of a painting | 2–3 days | Michalski (1991) |
| | Objects inside wooden transport cases | 2–3 days | Kamba (1994) |
| | 1-cm thick gilded plank/painting frame (reverse side free/unfinished?) | ±5–7 days | Michalski (1991) |
| | 1-cm wooden plank finished with varnish or paint | ±13 days | ASHRAE (2011) |
| | Film in steel container | ±15 days | Bigourdan et al. (1997) |
| Months | Book inside tightly closed bookcase | 2–3 months | ASHRAE (2011) |
| | Closed piece of furniture filled with buffer such as textiles | 3–4 months | ASHRAE (2011) |
| | Object stores inside sealed (air-tight?) plastic bag/box | 12–18 months | ASHRAE (2011) |

of furniture filled with buffering materials such as textiles. The relative humidity equilibration half-lives of several typical materials and objects are shown in Table 4.6.

Lowering the response time of objects should be seen as an effective preventive measure. Thus, for instance, climate control for a library collection kept inside a tightly closed glass case shall be less demanding than when the collection is on open display. This is a good argument to enclose highly vulnerable objects in a microclimate (cabinet, box or bag) for storage purposes. If the objects inside a closed volume consist of different hygroscopic materials it is recommended to add an extra amount of moisture buffering materials (Toishi and Gotoh 1994).

When using closed cardboard boxes for the storage of paper documents, exposure to very large temperature fluctuations should be avoided. Under these circumstances, hygroscopic materials will absorb and release moisture depending on their temperature. The response is initially strong and immediate, but as the cycles continue over time the amount of moisture that is absorbed and desorbed declines possibly due to a reduction in the materials moisture sorption capacity. As a result, the relative humidity inside the container increases. This process has been observed to occur with temperature cycles of relatively large amplitude; between 25 and 55 °C (Knop et al. 2007).

Objects with long response times experience a substantially different relative humidity than objects with short response times. This effect can be illustrated by considering the 'moving average' for different response times (Bratasz et al. 2007). To calculate the climate experienced by the object, the response can also be approximated using a first order approach, see Eq. 4.3 (Martens 2012).

$$RH_{response} = \frac{RH_{response,\quad i-1} \ + \ \frac{RH_i}{{}^{n}\!/_{3}}}{1 \ + \ \frac{1}{{}^{n}\!/_{3}}} \tag{4.3}$$

In which $RH_{response,i}$ the object's response to the relative humidity (%) is, for the first data point $RH_{response,i}$ is equal to $RH$, $RH$ the relative humidity (%), $i$ the current data point (−) and $n$ the number of data points in the response time (−).

Three different response times to relative humidity fluctuations are shown in Fig. 4.21. It is clear that, for longer response times the moving average changes only slightly, the relative humidity fluctuations are attenuated, and therefore the object experiences more stable conditions than other objects with shorter response times.

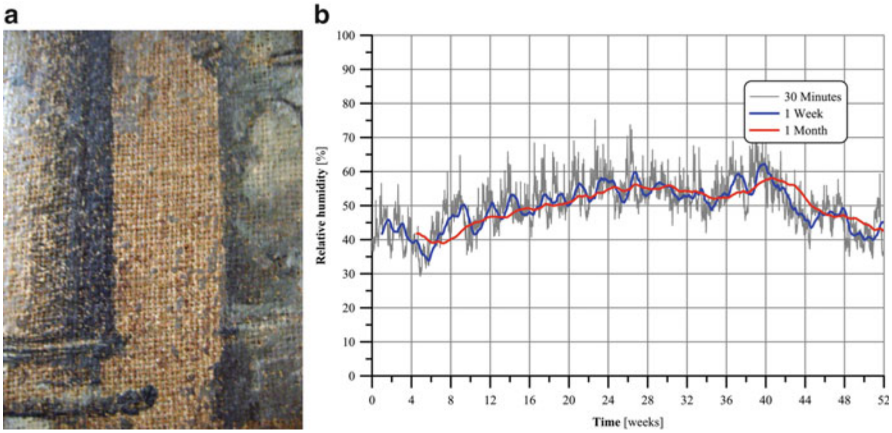

**Fig. 4.21** A canvas painting with missing paint (**a**), whereby the underlying fabric absorbs or releases moisture very quickly. This object has a response time of about 1–3 h. The graph (**b**) shows relative humidity readings taken every 30 min (*Grey Line*), and two curves with moving averages calculated for response times of 1 week (*Blue Line*) and 1 month (*Red Line*), respectively

The values obtained this way can be used to calculate the equilibrium moisture content of objects (Camuffo 2004). Because the risk of damage directly depends on the equilibrium moisture content, this parameter can be plotted against time to provide an indirect indication of dimensional changes undergone by the objects in response to relative humidity fluctuations.

For voluminous objects it should be taken into account that the surface reacts before the core can, resulting in internal stresses. Large objects require a long time, up to a few months, to fully equilibrate to new environmental conditions. When experiencing a relative humidity fluctuation, the surface will absorb or release moisture relatively fast thus creating a moisture gradient within the material (Schellen 2002). This gradient causes the development of internal stresses. For instance, shrinkage of the outer layer (due to moisture desorption) can be hindered by the core, which could lead to the formation of small hairline cracks on the object's surface (Kozłowski 2007). For polychrome objects, surface porosity and the degree of adhesion of the top layer to the core are the main factors determining whether or not this type of response will cause damage.

Larger cracks become visibly wider and narrower as the relative humidity fluctuates. This reaction occurs generally much faster than the time it takes for the entire object to equilibrate. A study involving a piece of furniture in an English historic house (Knight and Thickett 2007) has shown that, the width of a crack followed the relative humidity fluctuations with a delay time of approximately 40 h. No significant effect on crack width has been observed due to temperature changes, which ranged between 11 °C (52 °F) and 20 °C (68 °F). Very porous objects obviously absorb and release moisture much faster than objects with a non-porous surface. Therefore, in order to estimate the risk of relative humidity fluctuations, it is necessary to estimate the relevant duration of a relative humidity fluctuation per object.

Finally, the moisture diffusion coefficients in wood decrease with decreasing temperature and hence significantly increases the response time of objects to relative humidity variations (Rachwał et al. 2011). This effect can be one of the factors accounting for the frequent observation that wooden works of art usually remain in remarkably good condition over centuries in unheated historic buildings, such as the unheated hunting castle Moritzburg near Dresden without any form of humidity control (Schulze 2013).

## 4.5 Incorrect Temperature

Temperature plays an important role in chemical (and biological) deterioration processes. The rate of chemical reactions increases at higher temperatures. In principle, the lower the temperature, the longer the expected lifetime of objects and thus their usability in a museum context. Temperature also plays a role in physical-mechanical processes. Materials with a low melting point can become soft and deform at higher temperatures. On the other hand, some materials can become brittle at relatively low temperatures. A secondary effect of higher temperatures is moisture desorption from hygroscopic materials.

Based on these types of deterioration processes, three different risky situations can be considered:

1. The temperature is too high.
2. The temperature is too low.
3. The temperature fluctuates too much.

The material properties of a collection will ultimately determine to what extent it can be damaged by an incorrect temperature.

### 4.5.1 The Temperature Is Too High

Chemically unstable materials deteriorate faster than chemically stable ones. The question is how fast the reactions proceed, and how quickly material changes can be seen. The direct influence of temperature on the rate of chemical reactions can be estimated straightforwardly using the Arrhenius equation (see Eq. 4.4).

$$k = A \cdot e^{\frac{-E_A}{RT}} \tag{4.4}$$

In this equation, $k$ is the reaction rate constant ($s^{-1}$ for first order reactions), $A$ is the pre-exponential factor (same units as $k$), $E_A$ is the activation energy ($J.mol^{-1}$), $R$ is the gas constant ($8.314\ J.K^{-1}.mol^{-1}$), and $T$ is the temperature (in Kelvin, K).

Being inversely proportional to the reaction rate ($k$), the expected lifetime of materials or objects can be estimated from the Arrhenius equation. By choosing a reference lifetime of “1” at 20 °C (68 °F, 293 K), relative lifetimes at other temperatures can be calculated. Because in the case of museum collections, lifetime may not be the best practical measure for use in a museum context, it is preferable to talk about relative usability instead.

Analysis of experimentally determined activation energies for the deterioration of paper, film, magnetic media, and varnishes has shown that all values lie within the range of 80–120 $kJ.mol^{-1}$. Kinetic experiments studied the rate of silk deterioration and suggest the activation energy is approximately 50 $kJ.mol^{-1}$ (Luxford 2009). Using the midpoint of the activation energy range of 80–120 $kJ.mol^{-1}$ ($E_A = 100\ kJ.mol^{-1}$), the Arrhenius equation predicts that lowering the temperature by 5 °C (9 °F) doubles the expected lifetime (i.e. halves the reaction rate constant $k$). A useful rule of thumb, therefore, is that the usability of chemically unstable materials doubles for each 5 °C (9 °F) decrease in temperature under constant relative humidity (Michalski 2002). This is why photographic collections (particularly highly sensitive cellulose acetate and nitrate negatives) are often kept in cold storage (−20 °C/−4 °F). It should be noted that, for storage at very low temperatures, the expected usability is primarily determined by the time the collection

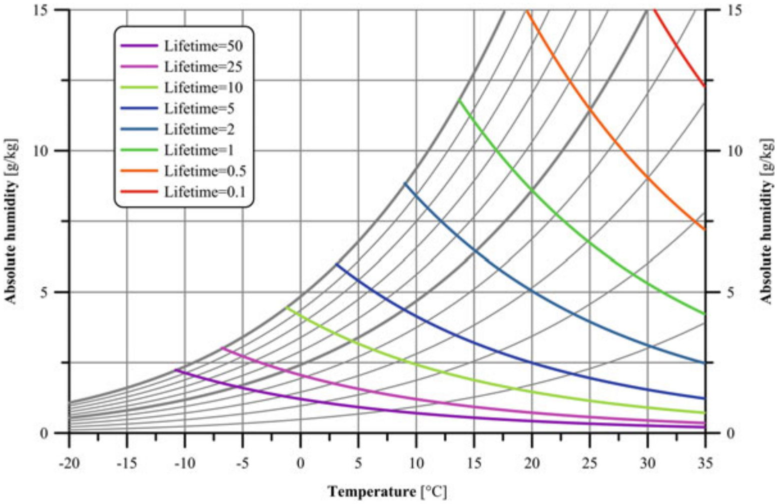

**Fig. 4.22** Lines of equal Relative Usable Lifetimes (RUL's) with respect to reference conditions (relative humidity = 50 % and T = 20 °C), plotted in a psychrometric chart, using $E_A = 100$ kJ.mol$^{-1}$ (Based on Michalski 2000)

remains out of storage. Lowering the temperature provides the highest gain in chemical stability; lowering the relative humidity at temperatures above 0 °C (32 °F) provides a significant gain, but that the retrieval frequency and the time the photographic material remains outside the cold storage conditions will ultimately determine which investment is justifiable. For a time-out-of-storage of less than 30 days/year on average, storage at −20 °C (−4 °F) is meaningful; for more than 30 days/year a storage temperature of 5 °C (41 °F) is sufficient.

Because the expected usability of objects does not depend exclusively on the temperature, it is necessary to consider the combined effect of temperature and relative humidity. Combining and rewriting Eqs. 4.2 and 4.4 into a new Eq. (4.5) allows expression of the reaction rate as a function of both temperature and relative humidity.

$$k_{total} = k_T \cdot k_{RH} = RH^{1.3} \cdot A \cdot \exp(E_A/RT) \tag{4.5}$$

This conversion is worked out in detail in appendix 5. Expected 'relative usable lifetimes' (RUL's) can be shown in a psychrometric chart (see Fig. 4.22). The reference value (RUL = 1) is indicated by the light green line, corresponding to a collection kept under a relative humidity of 50 % and a temperature of 20 °C. Figure 4.22 shows the expected relative usability increases as the relative humidity and the temperature decrease. So, for instance, the relative usability of a chemically unstable collection (see also Table 4.1) is increased by a factor of 5 (blue line in Fig. 4.22) in cool storage (+10 °C, 50 % relative humidity).

The effect of temperature and relative humidity on the relative usability presented in Fig. 4.22 should be seen as an indicator rather than as fixed values for conservation purposes. Not all chemically unstable or stable objects behave exactly the same, i.e. have similar activation energies. Therefore, the graph should be used as a rough indicator of the desirable indoor climate for optimal storage of chemically unstable materials.

### How Can an Old Newspaper Survive?

*A newspaper dated May 10 1940* (Fig. 4.23) *has, as a chemically unstable material* (see Table 4.1), *an expected lifetime of 30–100 years at 20 °C (68 °F) and 50 % relative humidity. After 100 years it is expected to become too brittle to be handled or exhibited. The question is, how many years can the newspaper's expected usability be prolonged by storing it, for instance, at 10 °C (50 °F).*

113DE JAARGANG

Nieuwe Amsterdamsche Courant

ALGEMEEN HANDELSBLAD

Vrijdag 10 Mei 1940

AVONDBLAD

No. 37104, Twaalf bladzijden

Nederland in oorlog met Duitschland

België, dat ook door Duitschland is aangevallen, en ons land hebben een beroep gedaan op de Geallieerden, die hebben toegezegd alle mogelijke hulp te zullen verleenen

Grenstroepen bieden verbitterd weerstand aan IJssel en Maas

Vannacht drie uur overschreden Duitsche troepen onze grenzen, ruim een uur later bombardeerde de Duitsche luchtmacht Nederlandsche vliegvelden en te zes uur bood de Duitsche gezant te 's-Gravenhage een verklaring aan, waarbij de inzet van een Duitsche troepenmacht werd aangekondigd en elke tegenstand doelloos

Duitschers of [illegible] van Duitsche afkomst verboden is zich in

PROCLAMATIE
VAN H. M. DE KONINGIN

Mijn Volk,

Nadat ons land met angstvallige nauwgezetheid al deze maanden een stipte neutraliteit had in acht genomen en terwijl het geen ander voornemen had dan deze houding streng en consequent vol te houden, is in den afgeloopen nacht door de Duitsche weermacht zonder de minste waarschuwing een plotselinge aanval op ons gebied gedaan. Dit niettegenstaande de plechtige toezegging, dat

**Fig. 4.23** Front page of the algemeen handelsblad newspaper dated 10 May 1940. How long can this paper be handled and used in a frequently accessed collection?

*Firstly, the age of the object is calculated: 2014 − 1940 = 74 years. Making the most optimistic assumption of an expected usability of 100 years, of which 74 years have already elapsed, the newspaper has an expected remaining usability of approximately 30 years at a relative humidity of 50 % and a temperature of 20 °C (68 °F).*

(continued)

*In cool storage, at 10 °C (50 °F), there is roughly a fivefold increase in the newspaper's expected lifetime, 30 × 5 = 150 years. Under these storage conditions, the object would stay usable until 2160 (2014 + 150). In cold storage (−10 °C/14 °F), the expected relative usability would be prolonged by a factor of more than 50. The newspaper from 1940 can then still be exhibited and accessed in the year 3600.*

*Contrarily, chemically unstable objects age (degrade) faster as the temperature increases. The same newspaper will therefore have its usability reduced twofold at an average storage temperature of 25 °C (77 °F) and 50 % relative humidity. If, for instance, it is exhibited inside a hot showcase, the newspaper will become unusable after half of the remaining 30 years at 20 °C (68 °F),* i.e. *before 2024.*

The argument provided by the concepts of isoperm and relative usability is being increasingly used for establishing indoor climate specifications for archives and libraries (Pretzel 2007). The Image Permanence Institute (IPI, Rochester, USA) has developed software to quantify the quality of the indoor climate in a simple way by means of a *time weighted preservation index*. Based on the uploaded climate data, the software indicates where the chemical and biological risks are. Only a very simplified picture of the risks is provided by the software. This is because the underlying model that describes the rates of chemical deterioration is based exclusively on experimental data collected for the chemical aging of cellulose acetate.

Next to chemically unstable materials, objects that are considered chemically stable can still undergo chemical changes. In the past decades much research has been done on the formation of metal soaps, darkening and pigment migration processes in oil paint. An overview of which is provided by van Loon et al. (2012). The reaction rate of these will be significantly influenced by the temperature, light dose, relative humidity and other factors such as the pigment volume concentration.

Another risk of a too high temperature occurs when the melting temperature or softening point of certain materials is reached. Under most northern hemisphere conditions, room temperatures are never much higher than ca. 35 °C (95 °F), which is much lower than the melting point of most materials. However, if sunlight falls directly on a dark surface the local temperature can reach up to 60 °C (140 °F). In equatorial/tropical climates room temperatures can be much higher, which will cause rapid deterioration of chemical unstable materials. And softening or even melting of materials with relative low melting points, such as waxes.

The risk of melting or severe softening of materials in a museum context is generally not particularly high. There are some materials such as wax statues and chocolate art pieces that can become soft at higher room temperatures (see also Fig. 4.24). This effect can be clearly seen by the warping of candles in historic interiors under the influence of high temperatures. A secondary risk for surfaces that are finished with coatings having low $T_g$, such as a wax layer, is the accumulation of

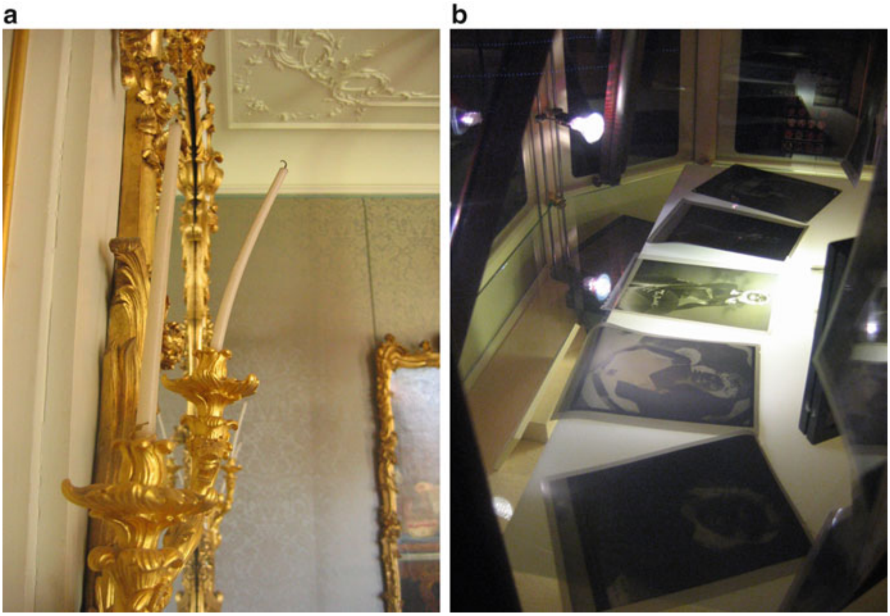

**Fig. 4.24** At relatively high temperatures certain materials become soft, such as candles (**a**), and/or age faster and deform, e.g. negatives (**b**)

dust and dirt that stick to the softer wax. Acrylic paints also pick up more dust at higher temperatures.

### 4.5.2 *The Temperature Is Too Low*

The advantage of low temperatures is that chemical reactions proceed more slowly. The degree of shrinkage or expansion experienced by lowering the temperature is relatively small for many materials (see ‘temperature fluctuates too much’ section).

There is, however, the risk that materials become brittle at lower temperatures. Polymers for example, change from a ‘rubbery’, more flexible state to a ‘glassy’, more easily breakable state at a given temperature. This transition temperature is called the glass transition temperature ($T_g$). If the $T_g$ of a material is close to the ambient temperature (for instance, under cold or cool storage), it can suddenly become much more vulnerable to mechanical damage as a result of a temperature fluctuation.

The $T_g$ of oil, alkyd, and acrylic paints, as well as of some plastics (polypropylene), is approximately 12 °C (54 °F). Hide glue and gelatin, on the other hand, are fully elastic within the temperature range of −10 °C (14 °F) to 27 °C (81 °F). For film materials, it has been established that they can be stored without any negative

**Fig. 4.25** A cobweb-like crack pattern in a painting, associated with mechanical impact at temperatures lower than the glass transition temperature (Photo: Burnstock, The Courtauld Institute of Art)

effect at a temperature of −20 °C (−4 °F) (Tumosa et al. 2001). Many plastics do experience some change in shape when stored at lower temperatures, which is fully reversible (Shashoua 2005). At room temperature an acrylic paint is much more flexible than an oil paint. The former is typically composed of an aqueous dispersion of copolymers of methyl methacrylate and the softer ethyl acrylate, to which different additives are incorporated. However, both low temperatures and low relative humidities make acrylic paint brittle (Jablonski et al. 2003).

Becoming brittle is not a problem in itself, but if brittle materials are handled they break more easily than flexible ones. An example of this behavior is the damage to paintings with a 'fresh' varnish at low temperatures, which cause the varnish to become susceptible to fracture (craquelure) if the canvas is exposed to mechanical impact. This so-called brittle fracture leads to the formation of cobweb-like crack patterns (see Fig. 4.25). Such a process seems particularly relevant for objects being transported, whereby they are exposed to low temperatures e.g. during high altitude flights.

### *4.5.3 The Temperature Fluctuates Too Much*

There are several ways in which a temperature fluctuation can occur. The most serious is when sunlight falls directly onto an object. Large temperature fluctuations can also occur near heating elements such as radiators and infrared emitters.

**Table 4.7** Coefficients of thermal expansion for various painting materials (Source: Richard 2007)

| Material | Linear thermal expansion coefficient ($\times 10^{-6}$ per °C) |
|---|---|
| White oak, *Quercus alba*, longitudinal | 0.3 |
| White oak, *Quercus alba*, radial | 32 |
| White oak, *Quercus alba*, tangential | 40 |
| Oil paint, white lead | 44 |
| Oil paint, yellow ochre | 64 |
| Oil paint, Naples yellow | 52 |
| Rabbit skin glue | 29 |
| Copper | 17 |
| Aluminum T-2024 | 23 |

Objects that exhibit large strain due to temperature fluctuations are vulnerable. Almost none of the materials in museum collections, however, experience a large enough strain in response to temperature changes to exceed their yield point and undergo damage. The dimensions of wood, paper, and canvas will not change significantly as a result of a temperature rise or fall.

The coefficients of thermal expansion of materials such as wood are very small, which means that this material can be stored under cold conditions see Table 4.7. Especially when the volume changes caused by temperature changes are compared to the relative humidity fluctuation needed to get the same volume change. A quarter-sawn one-meter-wide white oak panel in a well-sealed microclimate package will theoretically contract by 0.64 mm across the grain when the temperature drops from 20 to 0 °C (68–32 °F). For comparison, the same shrinkage would occur with a drop in relative humidity from 50 to 47.7 % (Richard 2007).

Practice has shown that many materials can be given a pest infestation treatment using low temperatures without causing mechanical damage due to temperature fluctuations. In Table 4.7 some thermal expansion coefficients of common painting materials are provided. The risk of mechanical damage due to temperature fluctuations might be high if two materials with very different thermal expansion coefficients are within the same (layered) fixed structure.

To conclude, the upper limit for temperature (25 °C/77 °F is recommended in the ASHRAE standard 55–2013) is generally determined by human comfort requirements, with the implicit acceptance of the risk of faster deterioration of chemically (un)stable materials. Wherever and whenever possible, it is recommended to accept lower temperatures for collection conservation purposes. During the heating season, the thermostat could be set at 17–18 °C (63–64 °F) without significantly compromising human comfort. This measure will also reduce energy consumption and saves on energy bills.

The lower temperature limit for a mixed collection could be defined as the glass transition temperature of the polymers in the collection, given the significant risk of physical damage that can be expected at and below this temperature. A lower limit for these materials would be a minimum temperature of 13 °C (55 °F).

## 4.6 Climate Classes and Risks

Risks to the collection can be identified and quantified when their causes and effects are known. The magnitude of risk is determined by the probability of an occurrence of a certain event or the rate at which a given deterioration process advances (chance), and by the resulting effect, consequence or impact.

The previous sections dealt mainly with the impact of an incorrect climate on the material properties of a movable collection. The probability of occurrence (and the rate) of damaging processes depends on the environmental conditions. Indoor climate hazards can be formulated as follows:

| | |
|---|---|
| The relative humidity | Is above 0 %; |
| | Is below or above a critical value; |
| | Is above 75 %; |
| | Fluctuates |
| The temperature | Is too high; |
| | Is too low; |
| | Fluctuates |

Knowledge about historic and current indoor climate conditions is required to assess the risks. By combining our understanding of the environmental conditions and the sensitivity of the collection, it is possible to estimate the magnitude of certain climate risks. Each building has its own indoor climate, and the conditions to which museum collections are exposed vary significantly. Even so it is possible to describe these different conditions in general terms, so that they can be useful to estimate the risks. By doing so, the different indoor climates must be sufficiently distinguishable to allow a meaningful categorization.

Different types of categorization of the indoor climate have been used in the Netherlands. The Central Government Real Estate Agency established its own guidelines for storage facilities with five climate classes for different conservation levels: strict, reasonable, minimal, none, and specific. This classification was primarily designed to clarify climate concepts wherein numerical clarity is desirable for all parties involved in the development of a schedule of requirements for museum construction, renovation, and redevelopment projects. By quantifying the temperature and the relative humidity, these climate classes can also be used to describe current and historic indoor climates. Our intention in the present publication is to adopt and link to the climate classes published in the ASHRAE Handbook. The different climate classes are therein designated by the letters AA, A, B, C, and D, and three specific storage conditions (cool, cold, and dry) are defined separately. These climate classes are presented in Table 4.8 and in appendix 7. The authors of this classification have used the notation AA, A, B, C, and D to express the level of risk of relative humidity fluctuations. The difference in the level of risk between classes A and B is significant, whereas between classes AA and A it

**Table 4.8** The different climate classes for the museum indoor climate (ASHRAE 2011). See Appendix 7 for a schematic overview

| Maximum fluctuations and gradients in climate controlled spaces | | |
|---|---|---|
| Climate class | Short fluctuations plus space gradients | Seasonal adjustments in climate control system set point |
| AA<br>Precision control, no seasonal changes (see Fig. A7.1) | RH: 5 % higher or lower | RH: no change |
| | T: 2 °C (4 °F) higher or lower | T: 5 °C (9 °F) higher or lower |
| A<br>Precision control, some gradients or seasonal changes (see Figs. A7.2 and A7.3) | RH: 5 % higher or lower | RH: 10 % higher or lower |
| | T: 2 °C (4 °F) higher or lower | T: 5 °C (9 °F) higher or 10 °C lower |
| | RH: 10 % RH higher or lower | RH: no change |
| | T: 2 °C (4 °F) higher or lower | T: 5 °C (9 °F) higher or 10 °C lower |
| B<br>Precision control, some gradients plus temperature adjustment in the winter (see Fig. A7.4) | RH: 10 % higher or lower | RH: 10 % higher or lower |
| | T: 5 °C (9 °F) higher or lower | T: 10 °C (18 °F) higher (but not above 30 °C/86 °F) or as low as necessary to maintain relative humidity control |
| C<br>Prevent all high risk extremes | RH: must not be below 25 % or above 75 % | |
| | T: below 25 °C (77 °F) and rarely over 30 °C (86 °F) | |
| D<br>Prevent damp | RH: reliably below 75 % | |
| Cold store<br>RH: 40 %<br>T: −20 °C (−4 °F) | RH: 10 % higher or lower | |
| | T: 2 °C (4 °F) higher or lower | |
| Cool store<br>30 % < RH <50 %<br>T = 10 °C (50 °F) | (Even if these conditions are achieved only during the winter by adjusting the temperature, this can be considered a net advantage to such collections, as long as damp is not incurred) | |
| Dry room<br>0 % < RH <30 % | The RH must not exceed some critical value, typically 30 % | |

is very small. Yet there are institutions that will still pursue the marginal benefit of AA over A (Michalski 2007).

The relative humidity set point or annual average (for climate classes AA to D in Table 4.8) depends on local factors. The value can be based on the historical annual average – i.e. the conditions that actually prevailed for the past years – for the permanent exhibition/storage facility. Generally a relative humidity around 50 % is used in many European countries. In Japan and UK a relative humidity set point of 55 % is more common. It is advised to choose an indoor annual average close to the annual average outdoors.

The historical annual average is a value that may differ from the fixed set point, or from the value contained in the schedule of requirements. Objects that have been on display for a long time in air-tight showcases with a heat source inside, could have adapted to a lower relative humidity than that of the room.

The set point or annual average temperature lies between 15 and 25 °C (59 °F and 77 °F). It should be noted that in rooms intended for loans, institutions must be able to maintain the conditions specified in the loan agreement. These are typically a relative humidity of 50 %, and a temperature of 21 °C (70 °F). Sometimes, however, the lender demands otherwise whether or not justifiably (Ashley-Smith et al. 1994).

Traditionally the requirements for the relative humidity were quite strict and based on the ICOM loan guidelines, dating from 1974 (ICOM 1974). These state that the relative humidity should be maintained at 54 ± 4 % in normal circumstances. There is no temperature specification, other than that during photography, the lighting should not raise the surface temperature of the loan with more than 3 °C (5 °F) above room temperature. In 2004 ICOM adjusted these requirements in "Running a Museum: a practical handbook" (ICOM 2004) where it is stated that "Risk management replaces rigid standards for the museum environment". From then on several discussions, conferences and roundtables were organized to discuss the set temperature and relative humidity guidelines for hygroscopic materials on loan. In 2009, the International Group of Organizers of Large-Scale Exhibitions, known as the 'Bizot Group' proposed a range of 40–60 % RH and 15–25 °C (59–77 °F). The National Museum Directors' Council (NMDC) representing the leaders of the UK's national collections and major regional museums basically copied these guidelines, but also stated that; "more sensitive materials (e.g. scroll paintings on silk, panel paintings, vellum or parchment) require specific and tight relative humidity control, specified according to the materials. Less sensitive materials (e.g. stone, ceramic) can have wider parameters for relative humidity and temperature".

In April of 2010, the Museum of Fine Arts in Boston and the Getty Conservation Institute in Los Angeles organized meeting with 60 representatives of large museums in North America and the UK, along with scientists working in the field of museum climate. The goal was to formulate environmental requirements for loans. The following basic principles were agreed on as a preliminary step towards an interim guideline: The majority of cultural materials, require a relative humidity set point in the range of 45–55 % with an allowable drift of ±5 %, i.e. 40 % < RH <60 % and a temperature range of 15–25 °C (59–77 °F) is acceptable. It is advisable to minimize fluctuations.

But, some cultural materials require different environmental conditions for their preservation. Loan requirements for all objects should be determined in consultation with conservation professionals. In 2012 the Bizot group again stated that the relative humidity is not permitted go out of the range 50 ± 10 %RH, nor is it allowed to change by 20 % during 1 day. In Germany however, the Doerner Institute published the so-called *Munich Position*, with 15 arguments why a relaxation of the climate guidelines for loans is dangerous (Burmester and Eibl 2013).

An overview of the international standards and specifications since the 1970s for temperature and relative humidity is provided by Bratasz (2012).

Climate classes AA, A, B, C, and D in Table 4.8 are distinguished by the different fluctuations and gradients. For the special storage spaces (cold, cool, or dry), the annual average set point is the distinguishing factor. It should be noted that the duration of short fluctuations varies from several hours to several weeks but is always shorter than the seasonal changes.

Using the information on the susceptibility of wooden objects, paintings and chemically unstable materials and the climate classes, the risks to the collection can now be assessed. Table 4.9 presents a short description of risks and benefits to the collection for each climate class.

**Table 4.9** Risks and benefits to the collection for different climate classes (ASHRAE 2011)

| Class of climate control | Collection risks and benefits |
|---|---|
| AA | No risk of mechanical damage to most objects and paintings. Some metals and minerals may degrade if the relative humidity of 50 % falls below or exceeds a critical relative humidity. Chemically unstable objects become unusable within decades |
| A | Small risk of mechanical damage to high vulnerability objects: no mechanical risk to most objects, paintings, photographs, and books. Chemically unstable objects become unusable within decades |
| B | Moderate risk of mechanical damage to high vulnerability objects. Tiny risk of damage to most paintings and photographs, some objects, some books. No risk to many objects and most books. Chemically unstable objects become unusable within decades or earlier if the temperature is routinely at or above 30 °C. Cold winter periods, however, will prolong usability (lifetime) |
| C | High risk of mechanical damage to high vulnerability objects. Moderate risk of damage to most paintings, most photographs, some objects, some books. Tiny risk to many objects and most books. Chemically unstable objects become unusable within decades or earlier if the temperature is routinely at or above 30 °C. Cold winter periods, however, will prolong usability (lifetime) |
| D | High risk of sudden or cumulative mechanical damage (fracture) to most objects and paintings due to low relative humidity. Delamination and deformations, especially in veneers, paintings, paper and photographs due to high relative humidity will be avoided. Mold growth and rapid corrosion is avoided. Chemically unstable objects become unusable within decades or earlier if the temperature is routinely at or above 30 °C. Cold winter periods, however, will prolong usability (lifetime) |
| Cold store | Chemically unstable objects remain usable for millennia. Relative humidity fluctuations shorter than 1 month do not affect most properly packaged records at these temperatures. The time out of storage becomes the lifetime determinant |
| Cool store | Chemically unstable objects remain usable for a century or more. The types of documents usually stored this way in libraries and archives (paper, negatives and photographs) often have low mechanical vulnerability to fluctuations |
| Dry room | Archaeological metals remain usable for centuries |

In a risk analysis, scenarios are developed to describe the damage processes from the source of the agent of deterioration (incorrect relative humidity or incorrect temperature) to the final effect – the loss of value of the collection. The risks (and benefits) listed above relate to the prevailing or desired indoor climate conditions. There are also risks that arise as a direct consequence of the implementation of climate control.

It should be assumed that the risk of a short and severe climate fluctuation increases significantly with the introduction of a climate control installation and structural modifications in the building. Research has shown that five such incidents have occurred in the period of 1997–1999 in a population of 20 Dutch museums (Pennock 2000). This risk is particularly relevant if the climate control installation is under-sized, which means that it must operate continuously at full capacity. Under extreme outdoor conditions, be it too hot in the summer or too cold in the winter, the installation has the highest risk of malfunction. Two risks can be distinguished:

- The humidifier breaks down during a cold period and, as a result, dry air is blown into the collection areas. Mitigation of this risk is done by immediately switching off the HVAC system or switching to full recirculation. On December 23, 2005, such an incident occurred in a storage area full with hygroscopic materials. The relative humidity decreased from 50 to 40 % (new steady state) within 5 days. Then, with the repair of the climate control installation, it returned to 50 % in 1 h (Martens 2007).
- The cooling system breaks down during a hot period and, as a result, warm and humid air is blown into the collection areas.

Another relevant risk related to the implementation of an HVAC is the risk of water damage. There are many examples of water incidents in cultural heritage institutions resulting from improper operation of the climate control installation, often related to maintenance activity.

## 4.7 Conclusion

The most general conclusion to be drawn from the work presented in this chapter is that there is not one specific climate that reduces all risks, to all types of collections. Research has indicated that the trend of strictly controlled museum climates has, since the 1980s, changed to more relaxed specifications. The aim for chemically unstable collections is long-term preservation targets and acceptance of seasonal changes and broader ranges of short-term fluctuations and gradients. Studying objects in-situ showed that many objects have survived remarkably well in conditions that were far from the classical ‘ideal’, which shows us that strict climate specifications for objects is not required per se.

The result of this step is an overview of the collection anatomy with an indication which of the collection units or objects are susceptible to which aspect of the indoor climate. A table can be developed to visualize this relation. An example is provided in Table 4.10. from such a table the specific temperature and relative humidity set points and acceptable fluctuations can be developed and specified for each season.

**Table 4.10** The relative importance of controlling a specific climate parameter of the indoor climate for different types of collections

| | Temperature | | Relative Humidity | |
|---|---|---|---|---|
| | Set point | Fluctuations | Set point | Fluctuations |
| **Paintings on canvas** | Small risk of chemical degradation | Not relevant | Small risk of chemical degradation | Risk of mechanical degradation |
| **Wooden statues** | Small risk of chemical degradation | Not relevant | Small risk of chemical degradation | Risk of mechanical degradation |
| **Works on paper** | Risk of chemical degradation | Not relevant | Risk of chemical degradation | Small risk of mechanical degradation |
| **Textiles** | Small risk of chemical degradation | Not relevant | Small risk of chemical degradation | Small risk of mechanical degradation |
| **Bronze sculptures** | 🟩 | 🟩 | Small risk of chemical degradation | 🟩 |

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# Chapter 5
# Step 4: Assessing Building Needs

**Abstract** In this chapter the most relevant deterioration phenomena that have a strong relation with the indoor climate for (historic) buildings are described: moisture related problems, wood decay, wood infestation, salt attack, frost damage, corrosion and thermal expansion. For all of these phenomena, and the building as a whole, the ideal indoor climate is summarized.

**Keywords** Moisture related problems • Wood decay • Wood infestation • Salt attack • Frost damage • Decorative finishes

## 5.1 Introduction

Historic building fabrics require an indoor climate that reduces the risks of biological, chemical and mechanical damage to acceptable levels, very similar to the needs of the collection described in Chap. 4: step 3. The building is the first barrier between the outside climate and the collection indoors. The hygrothermal properties of the building envelope determine the indoor climate as described in Chap. 7: step 6. Besides providing a shelter to the outside climate, the envelope itself can also be exposed to risks that might cause a loss of (cultural) values. Architectural details inside the building can deteriorate due to a high relative humidity (e.g. fungal attack) and historic finishes can be damaged by large relative humidity fluctuations. So finding the climate needs for the building requires a similar understanding of the specific climate risks to the building envelope, and its interior finishes, as for the collection.

## 5.2 Moisture

Relatively large amounts of water can be absorbed by the building fabric. In the event of building defects, like roof and gutter leaks, substantial amounts of moisture can end up in the walls. Obviously, leaks are often directly related to poor maintenance (quality of craftsmanship and frequency) and/or the poor design of the construction. It is without doubt that these two causes are responsible for the

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majority of moisture related damage. This aspect is outside the scope of this publication and for further reading we refer to Cook and Hinks (1992).

Deterioration of the building envelope is primarily caused by an imbalance in the cyclic wetting and drying process. If a balance is maintained, moisture will not accumulate or reduce over time and moisture related risks are generally low. The natural outdoor sources of moisture that end up in the building's envelope are driving rain and rising damp from ground water. Most porous building materials will absorb this water, but to a different extent. The ability to absorb and transport moisture is related to the pore size, which determines the capillary suction efficiency. The smaller the radius of the pores, the more efficient the suction and thereby the more effective the transport of water. Vulnerable materials like soft brick, or some types of natural stone with a great amount of small pores, can absorb and hold a significant amount of water. This can be illustrated by comparing the amount of moisture in 1 $m^3$ of air, brick and wood. When the indoor air has a temperature of 22.5 °C (72.5 °F) and 50.1 % relative humidity, the air holds 0.01 L of water, aerated concrete about 11 L (EMC 2.4 m%), calcium silicate brick some 15 L (EMC 0.75 m %) and Eastern white pine approximately 32 L (EMC 7.0 m%). These calculations are based on Kumaran et al. (2006). For every (building) material an optimal upper and lower Equilibrium Moisture Content (EMC) limit can be determined. This optimum varies for different materials and will also vary per material property. For instance many mechanical properties of wood are affected by changes in moisture content below the fiber saturation point (Forest Products Laboratory 2010) and thermal conductivity increases as the moisture content increases (Ochs et al. 2008).

If the annual drying is larger than the annual wetting, the interior will (slowly) dry. The associated risk will be relatively low as long as the EMC does not fall below a critical lower limit of approximately 7–8 %. Below this value hygroscopic materials will shrink and might develop stresses, which are larger than the strength of the construction/material. This will result in permanent deformation, or even cracking. If the annual wetting is larger than the annual drying, the EMC of all hygroscopic materials in the building will increase and several problems might occur. The specific type, construction and quality of the building materials will ultimately determine the risk of moisture. Wood will rot when the EMC is too high, see Sect. 5.4. The risk of efflorescence is significant when the moisture content of salt loaded building materials fluctuates too much, see Sect. 5.5. The risk of freeze-thaw cycles for concrete, stone and brick will be high when the moisture content of these materials is too high and outdoor temperatures are below freezing point, for more details see Sect. 5.6. Concrete is often reinforced and the steel rebar can corrode if water content is too high (Sect. 5.7).

### 5.2.1 Wood Decay by Fungi in Buildings

Fungus is a collective term for a wide variety of microorganisms of which there are over 200,000 species. These include mold, yeast, mushrooms, lichen and truffles.

These micro-organisms are everywhere, they enter a building directly or by their spores being carried in by the air. In a home or building, molds and fungi are usually found growing on wood, drywall, wallpaper, drapery, ceiling tiles, and carpeting if the local conditions are rather damp. The effect of mold and fungus on the building involves the breakdown of organic matter and staining of surfaces.

In buildings the risk of surface mold growth, as described in Sect. 4.3.2, is in fact of little significance. Although surface mold growth is a problem on historic objects in collections, they hardly affect building materials apart from some discoloration of the interior finishes (Sect. 4.2.3). In buildings mold growth manifests itself as mostly black or dark brown stains on walls, especially in corners. However it is still a good indicator for moisture related problems. Fungal attack of wooden building components on the other hand can pose a major threat to the building, as it might affect the structural stability of beam ends, wall plates, and to a lesser extent of framed walls, trusses, lintels etc. and thus endanger public safety and heritage collections. It may also lead to a significant loss of authentic building fabric, signs of traditional craftsmanship and important or original features and thus cultural values.

Fungal growth can be described as either wet or dry rot (BRE 1989) or as brown and white rot (Ridout 1999). This subdivision is schematically presented in Fig. 5.1. Dry rot is always a brown rot species called *Serpula lacrymans*. This species digest parts of the wood which give the wood strength and stiffness, resulting in a dark colored deteriorated and cracked condition. Wet rot can be subdivided in brown and white rot fungi. Brown rot refers to a wood decay process caused by certain species of fungi that break down hemicelluloses and cellulose. The wood gets a dark or brown, crumbly appearance and loses its strength and stiffness. In many cases a relative sound outer surface is maintained. It will easily be reduced to dust and powder when crushed between fingers. Timber weight loss may be up to 70 % (Zabel and Morrell 1992). White rot breaks down hemicelluloses and cellulose and lignin. The wood will become lighter in color and the wood fibers will become clearly visible. The weight loss may be up to 95 % but the wood will not be reduced to powder (Zabel and Morrell 1992).

### 5.2.2 Typical Species

Brown rot and wet rot are caused by various species of fungus. Each of them can be found on typical locations as described in Fig. 5.1. In buildings the most serious type of decay is caused by dry rot which is caused by the fungus *Serpula lacrymans* (BRE 1993).

| **Fungus** | **Typically found in** |
|---|---|
| Dry rot fungus (*Serpula lacrymans*) | timber in contact with wet brickwork |

| **Fungus** | **Typically found in:** |
|---|---|
| Cellar fungus (*Coniophora puteana*) | very damp locations |
| Marmoreus cellar fungus (*Coniophora marmorata*) | floors, cellars |
| White pore fungus (*Antrodia vaillantii*) | locations with higher temperature |
| (Reddish) sap polypore (*Poria placenta*) | idem. |
| Yellow polypore (*Antrodia xantha*) | idem. |
| Jelly spot fungus (*Dacrymyces stillatus*) | exterior joinery |
| Stag's horn fungus (*Lentinus lepideus*) | skirting boards |
| Inkcap fungus (*Coprinus* spp.) | laths |
| Stalkless paxillus (*Paxillus panuoides*) | very wet locations |
| Ptychogaster rubescens | timber in contact with wet brickwork |

| **Fungus** | **Typically found in:** |
|---|---|
| Oak rot fungus (*Donkioporia expansa*) | ends of large oak beams embedded in walls |
| Cramp balls (*Daldinia concentrica*) | hardwood floors, particular sport halls |
| *Asterostroma* spp. | skirting boards |
| *Phellinus contiguus* | exterior joinery |
| Oyster fungus (*Pleurotus ostreastus*) | chipboard |

**Fig. 5.1** Schematic overview of the most commonly found fungi in buildings and their locations

### *5.2.3 Limits for Growth*

Buildings in which wooden elements become damp have a high risk of biological attack. The risk of fungal attack in a building depends on several factors: (i) the species of wood, (ii) the proportion of sapwood, (iii) the design and maintenance of the building and (iv) high indoor moisture load due to climatization.

Some woods, like oak, have a natural resistance to fungal attack. The wood moisture content can easily be above 20 % for many years without a significant risk. Other woods like modern pinewood are particular susceptible to fungal attack. A wood moisture content over 22 % for more than 2 months may already result in fungal attack. Woods with a large portion of sapwood are more vulnerable to fungal attack because these lack toxic extractives. A local high relative humidity, often combined with low ventilation at the wood surface, will result in a high (local) EMC of the wood. In properly designed and well maintained buildings the wood moisture content is typically beneath the threshold for fungal growth, i.e. 20 %.

The lower relative humidity limit at which fungal growth in buildings is not expected, is approximately 70 %. At 80 % relative humidity the growth for nearly all species is possible. The optimal range for growth is between 90 and 96 % relative

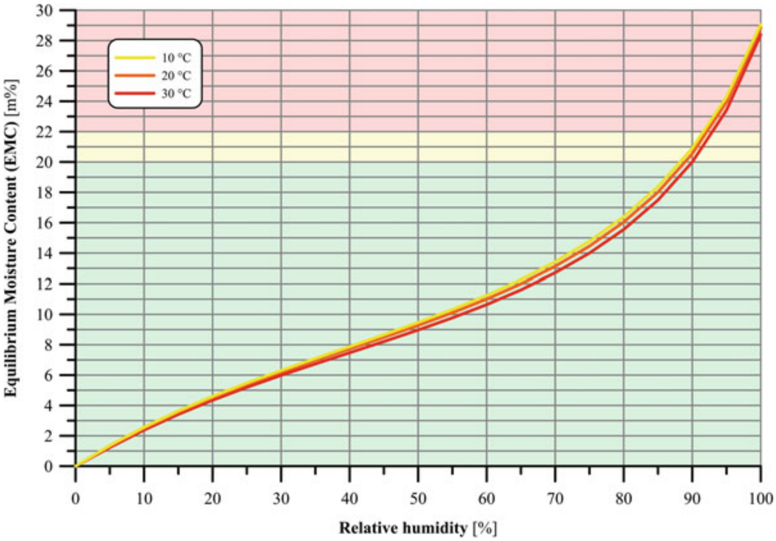


**Fig. 5.2** A hygroscopic curve for wood plotted for three temperatures: 10 °C (50 °F, *yellow line*), 20 °C (68 °F, *orange line*) and 30 °C (86 °F, *red line*) (based on the Hailwood-Horrobin equation, https://en.wikipedia.org/wiki/Equilibrium_moisture_content). The *green* area is supposed to be safe, the *yellow* area is to be avoided and the *red* area is dangerous

humidity. The associated EMC of wood, at the surface, or the core, determines the risk of rot. Rot requires an elevated EMC of 28–30 mass% to initiate fungal growth. i.e. the germination of spores. Once initiated, fungi can remain active in wood with an EMC of 22 % and above (BRE 1989). In Fig. 5.2 a hygroscopic curve for wood is plotted for three temperatures: 10 °C (50 °F), 20 °C (68 °F) and 30 °C (86 °F). As can be seen from this figure, the local relative humidity near the wood surface needs to be higher than 89.0–92.5 % to maintain a local EMC of 20–22 %. Aged wood has a slightly lower EMC. Brown rot results in a decrease of the EMC, white rot does not affect the hygroscopicity (Unger et al. 2001).

Next to the moisture conditions, temperature also plays a role in fungal growth. Fungi start to grow at temperatures above 0 °C (32 °F). The optimal temperature for growth can be over 30 °C (86 °F) (Seldbauer 2006). Some fungi can even grow at 50 °C (122 °F). In Table 5.1 temperature and moisture requirements are given for various wood damaging species. Since indoor temperatures will always be between 0 °C (32 °F) and 30 °C (86 °F), fungal growth will primarily depend on the wood moisture content due to building defects, or a high (local) relative humidity.

### *5.2.4 Control of Wood Rot*

Because wood rotting fungi generally do not grow in relatively dry wood, the most effective prevention is a wood moisture content below 20 %. Proper maintenance

**Table 5.1** Temperature and wood moisture requirements on mycelial growth of wood-rotting fungi (Unger et al. 2001)

| Fungus | Temperature [°C (°F)] | | | Wood moisture content [%] | | |
|---|---|---|---|---|---|---|
| | Min. | Optimum | Max. | Min. | Optimum | Max. |
| Cellar fungus (*Coniophora puteana*) | 0–5 (32–41) | 20–32 (68–90) | 29–40 (84–104) | 20 | 50–60 | |
| Dry rot fungus (*Serpula lacrymans*) | 0–3 (32–37) | 17–23 (63–73) | 28 (82) | 20 | 30–40 | 40–60 |
| White pore fungus (*Antrodia vaillantii*) | | 26–27 (79–81) | | 20 | 35–45 | |
| Yellow-red gill polypore (*Gloeophyllum sepiarium*) | 5 (41) | 26–35 (79–95) | | 20 | 38–60 | |
| Stag's horn fungus (*Lentinus lepideus*) | 8 (46) | 27–33 (81–91) | 38 (100) | 20 | 30–40 | |
| Stalkless Paxillus (*Paxillus panuoides*) | 5 (41) | 23–30 (73–86) | 29 (84) | 20 | 35–70 | |

and good design of building details is of great importance in order to avoid fungal attack in the building. Surface and interstitial condensation needs to be avoided at all times. In countries with low outdoor temperatures humidification in winter time is obviously the most relevant cause for these condensation processes. As can be derived from Fig. 5.2 the surface relative humidity needs to be on average below 92 % in order to keep the moisture content below 20–22 %. Low indoor temperatures and accepting a seasonal adjustment for the relative humidity to 40–45 % in winter, will reduce the risk of biological attack significantly.

The sources for the ingress of water into the building can be many. The most obvious ones are insufficient capacity of gutters, poorly detailed gutters and pipes with insufficient capacity. But also gutters full of leaves, overflowing gutters, poor pointing, shifted roofing tiles etc. can lead to excess water penetration over time.

To prevent the outbreak of wood rot, including dry rot, two types of measures can be taken: primary measures to prevent further outbreak and secondary measures to treat subsequent risks are given in Table 5.2.

## 5.3 Salt Attack

Along with air pollution, soluble salts represent one of the most important causes of stone and plaster decay in almost all parts of the world, particularly in urban, industrial and marine environments (Doehne and Price 2010). Salts are ionic compounds formed between positively charged ions, such as sodium ($Na^+$) and the negatively charged anions, such as chloride ($Cl^-$). In the built environment many different combinations of ions and anions, i.e. types of salts can be found,

**Table 5.2** IPM measures for controlling an outbreak of wood rot (Based on BRE Digest 345, 1989 and BRE Digest 299, 1993)

| | |
|---|---|
| Avoid | Locate and eliminate sources of moisture; |
| | Plan proper maintenance; |
| | Plan adequate ventilation; |
| | Keep moisture loads in winter low; |
| | Promote rapid drying of the structure |
| Block | Install adequate moisture barriers in insulated double walls |
| Detect | Plan inspections annually; |
| Confine | Contain the fungus within the wall (applies to dry rot only); |
| Treat | Determine the full extent of the outbreak; |
| | Remove rotted wood; |
| | Treat remaining sound timbers with preservative (if moisture content >21 % or in contact with dry rot affected masonry); |
| | Use preventive treatment replacement timbers |

including chlorides, sulphates, nitrates and carbonates. Commonly occurring salts are halite (table salt or sodium chloride; NaCl), gypsum (calcium sulphate: $CaSO_4$) and sodium sulphate ($Na_2SO_4$). Some types like, $Na_2SO_4$ and $MgSO_4$ are known to be more damaging than others like $NaNO_3$, NaCl and $CaSO_4$ (Lubelli 2006).

### 5.3.1 Damage Mechanism

The risk of salt damage is often first noted when an efflorescence is formed on the surface of the building (Fig. 5.3a, b). These white salts may be perceived as discrete crystals, a powder-like layer, or a bit more greasy substance. When crystals are formed inside the stone, a loose powdery surface can be observed. In extreme cases, the mortar will disintegrate and allow downwards stacking of the bricks. Damage caused by sodium chloride (NaCl) often appears as powdering of the outer layer where most of the salts accumulate.

The reason salts pose a problem to many porous materials is because they are soluble. At high relative humidity they dissolve and at low relative humidity crystallize. Crystallization at the surface is generally visible by the formation of crystals. These are not only formed at the surface but will also be formed within the pores of the stone. Salt crystals will be formed at the point of evaporation. The point of evaporation depends on the rate of evaporation of water vapor and the supply of liquid water from the core. If the rate of evaporation is smaller than the supply of liquid water, the point of evaporation is at the surface of the material. If the rate of evaporation is larger than the supply of liquid water, the point of evaporation is within the material. This crystallization of a single salt, or a mixture of salts, is accompanied by a volume increase. This generates stresses that are sufficient to overcome the stone's, or surface decoration layer's, tensile strength, which causes

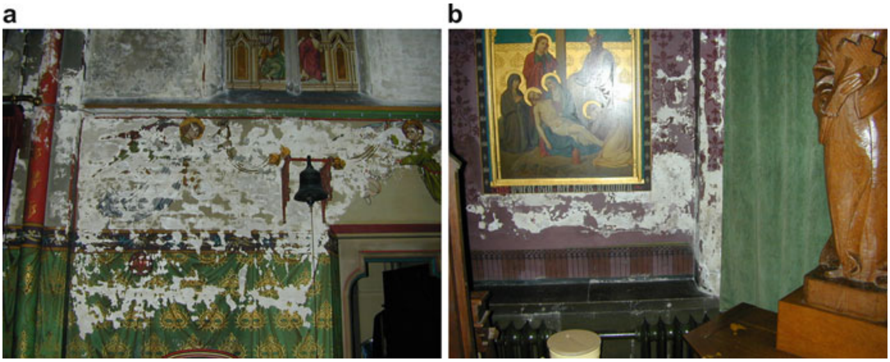


**Fig. 5.3** Salt efflorescence near the surface of a catholic church in the Netherlands severely damaging the wall painting (**a**) and a common cause the heating system (**b**) near the surface causing high temperatures and low relative humidity

cracking, scaling or spalling, or turning it into powder (Evans 1970; Charola 2000). Hence, unfavorable environmental conditions may cause evaporation and repeated cycles of dissolution-crystallization or hydration-dehydration, which can lead to the decay of building materials (Desarnaud et al. 2013; Shahidzadeh-Bonn et al. 2010; Espinosa Marzal and Scherer 2008; Steiger 2005; Scherer 2004; Lubelli et al. 2004). For the dissolution of salt crystals at greater depths inside the porous materials, longer and higher fluctuations are required. This implies that the dynamics of dissolution-crystallization cycles in building materials is strongly affected by both frequency and amplitude of the humidity variation as well as the moisture exchange properties between the materials and the environment (De Clercq et al. 2014).

Decay patterns depend on material properties, such as pore size, mechanical strength and the ability to transport moisture (Scherer 2004; Coussy 2006) and on boundary conditions, such as moisture supply, salt load, salt distribution and environmental conditions (Rodriguez-Navarro et al. 2000).

Salts near the surface react rapidly to a changing indoor relative humidity. So even fast and short term relative humidity fluctuations might cause their dissolution and re-crystallization. Lubelli (2006) observed that there is a strong correlation between the relative humidity fluctuations and debris falling from the wall. Damage only became visible in periods of high ambient relative humidity. Although the crumbling of stone occurred during times of low relative humidity. The dissolution of salts at high relative humidity caused the cemented debris particles to loosen and fall off.

### 5.3.2 *Location of Salt Damage*

Salt damage does not occur only in an outdoor environment, where the stone is subjected to cycles of rainfall and subsequent drying. For new buildings it is very common that new masonry shows efflorescence just after the building is completed (Fig. 5.4). This white efflorescence often contains lime leaching from the lime mortar, or lime or sulphates from the brick. This will disappear after a period of time.

Efflorescence can also take place indoors. Severe damage to stonework held in uncontrolled museum environments (Hanna 1984; Rodríguez-Navarro et al. 1998) or churches (Larsen 2007) is not uncommon. The amount of salt transported through the wall and the pore size will determine the severity of damage to the stone and the surface layers.

Concentrations of hygroscopic salts, which are often found in masonry, can also absorb extra moisture from the air. This means that a material can hold more water than might be expected according to the hygroscopic curve and the ambient relative humidity. In a room with fluctuating relative humidity levels, this can result in the regular appearance of efflorescence, i.e. salt blooms on the surface. This will change the appearance of the (valuable) surface. But even when no salts are visible, walls might appear wet at random places (Fig. 5.5).

**Fig. 5.4** After the construction is complete efflorescence can become visible (Photo: Kemper, FHB Gevelreiniging)

**Fig. 5.5** Wet spots on wall due to the absorption of water vapor by local high salt loads in the masonry (Photo: Van Hunen, Cultural Heritage Agency of the Netherlands)

### *5.3.3 Sources of Salt Contamination*

A wide variety of salts and their mixtures coming from different sources can be found indoors. The most common salt sources found in historic houses are summarized in Table 5.3. Air pollution is a major source of sulfates and nitrates. Other sources include the soil, from which salts may be transported into the masonry by rising damp. Salts can also be transported by air, e.g. from the sea (chlorides) or the desert. Other sources include deicing salt, unsuitable cleaning materials, incompatible building materials, garden fertilizers, and, in the case of some medieval buildings, the storage of gunpowder or kitchen salt (chloride) used for meat preservation. In some cases salt loaded stones, or coral taken from the ocean, was used to construct walls.

### *5.3.4 Assessing the Risk of Salt Contamination*

In order to assess the risk of salts and to design a proper risk treatment strategy, it is helpful to know more about different aspects of the mechanism leading to damage. Relevant information that can be obtained by looking at the specific salt loaded location, includes:

**Table 5.3** Source of some common ion

| | Salt | Common sources |
|---|---|---|
| Cations | Calcium ($Ca^{2+}$) | Building stone, mortar, groundwater, fertilizer |
| | Magnesium ($Mg^{2+}$) | Dolomitic limestone, de-icing salts, fertilizers, sea spray |
| | Potassium ($K^{+}$) | Groundwater, conservation treatments (particularly waterglass), manufacture of gunpowder, chemical removal of tree stumps |
| | Sodium ($Na^{+}$) | Groundwater, conservation treatments, cement, sea spray, de-icing salts, food preservatives, detergents |
| | Ammonium ($NH_4^{+}$) | Groundwater, polluted air, conservation treatment, explosives, fertilizers |
| Anions | Carbonates ($CO_3^{2-}$) | Limestone, groundwater, de-icing salts, wood ash, detergents |
| | Chlorides ($Cl^{-}$) | Groundwater (near source of sodium chloride), sea spray, de-icing salts, calcium-chloride concrete additives, pesticides, breakdown of plastics |
| | Nitrates ($NO_3^{-}$) | Groundwater, biological decay, manufacture of gunpowder, nitrifying bacteria, fertilizers, explosives, food preservatives, chemical remover of tree stumps |
| | Oxalates ($C_2O_4^{2-}$) | Formed by reaction of calcite in stone with oxalic acid released by certain types of microbes, or from hydrocarbon pollutants (the mechanism of formation is disputed) |
| | Sulphates ($SO_4^{2-}$) | Building stone, clay-based building materials such as brick, cement and concrete, gypsum based building materials, groundwater, polluted air, sea spray, fertilizer |

Source: English Heritage (2014)

- The type of salt (mixture);
- In case of a salt mixture, the ion ratios;
- Distribution of salts in height and depth;
- Moisture content;
- Environmental conditions such as rain, sun, wind, temperature, relative humidity and air flow.

If there is a suspicion that (part of) the building is contaminated with salts, a relatively simple test, such as, electric conductivity, can help determine the extent of salt loading. A sample is taken from the salt loaded surface, of which an aqueous extract is made, and the conductivity is determined.

The conductivity of the extract is directly related to the concentration of salts present in the solution. If several samples, taken from different locations throughout the building or room are prepared and analyzed, the results will provide a rough indication of where salt contamination is present and where is (most) severe. This first screening will help select zones for a more detailed salt contamination examination if needed. The electric conductivity is a quantitative test that will give a rough indication whether or not a sample is salt contaminated. The electrical conduction is often measured in Siemens per unit of length [S/m, $A^2 \cdot s^3 \cdot kg^{-1} \cdot m^{-3}$]. A general classification of conductivity ranges for salt loaded stone-like materials is provided by Groot et al. (2012):

| | |
|---|---|
| <500 μS/cm | No salt load; |
| 500–1,200 μS/cm | Light salt load; |
| 1,200–2,100 μS/cm | Moderate salt load; |
| 2,100–4,000 μS/cm | High salt load; |
| >4,000 μS/cm | Very high salt load |

Note that the salt load in itself is not an indicator for damage, but a first hint of a possible risk

The next step would be to investigate the moisture transport mechanism, to understand the driving forces that lead to salt related damage. To understand the mechanism it is essential to know where the moisture comes from, if moisture is accumulating in the building fabric and where the moisture evaporates.

This information can be combined with the results of the salt load measurements (vide infra) to assess the driving forces, such as low indoor relative humidity due to heating or dehumidification, or high capillarity due to driving rain, capillary sorption and leaks that are causing salt damage.

Both the moisture content of individual building components, and the distribution and amount of different ions, might vary in depth and height. The most challenging aspect of the analysis is to sample in such a way that the results are meaningful and representative of the risk. Note that the distribution and concentration of salts will only be representative for the time of sampling. Recording the ambient temperature and relative humidity is important. Efflorescence is the least problematic to sample. Scraping and brushing makes collection of samples relatively easy. To sample the subsurface or 'core' of a wall or floor, a slow rotating drill is needed and the bit must be cooled regularly. The method is standardized and described in Rilem commendation MS-D.10 Measurement of moisture content by drilling. Typical samples are collected at three depths:

| | |
|---|---|
| 0 cm | Surface |
| 5 cm | Subsurface |
| ≥10 cm | 'core' |

The location in the horizontal and vertical plane (height) depends on the appearance of the efflorescence, or the presence of wet surfaces. In Fig. 5.6 a typical measurement plan is provided. Each location is numbered and exact locations are marked.

Depending on the measured profile, the driving forces can be assessed. A schematic presentation of these moisture profiles in a wall, are presented in Fig. 5.7.

In order to determine at what relative humidity solid crystalline salts will dissolve and vice versa information about the composition is essential. The presence of nitrates, sulphates, and/or chlorides can be relatively easy determined by test strips. This method will only indicate the anions present in the mixture and is of limited accuracy. It cannot be considered as an adequate indicator for the crystallization behavior of mixed salt solutions. To determine the types of salts present in samples lifted by powder drilling at different heights and depths, techniques such as X-ray Diffraction (XRD) or X-ray Fluorescence (XRF) are generally used. A quantitative evaluation of the salt load can be obtained by the determination of

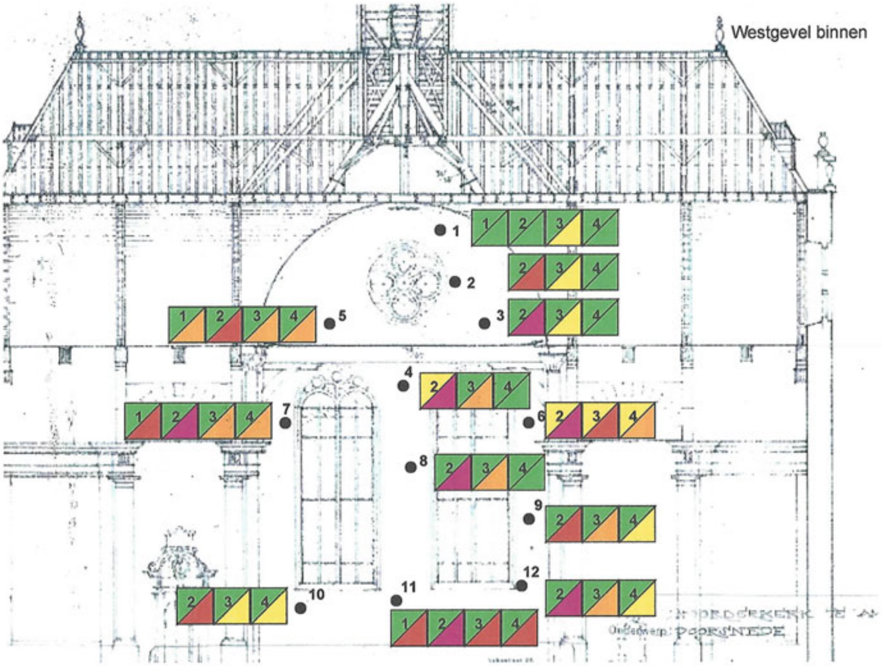


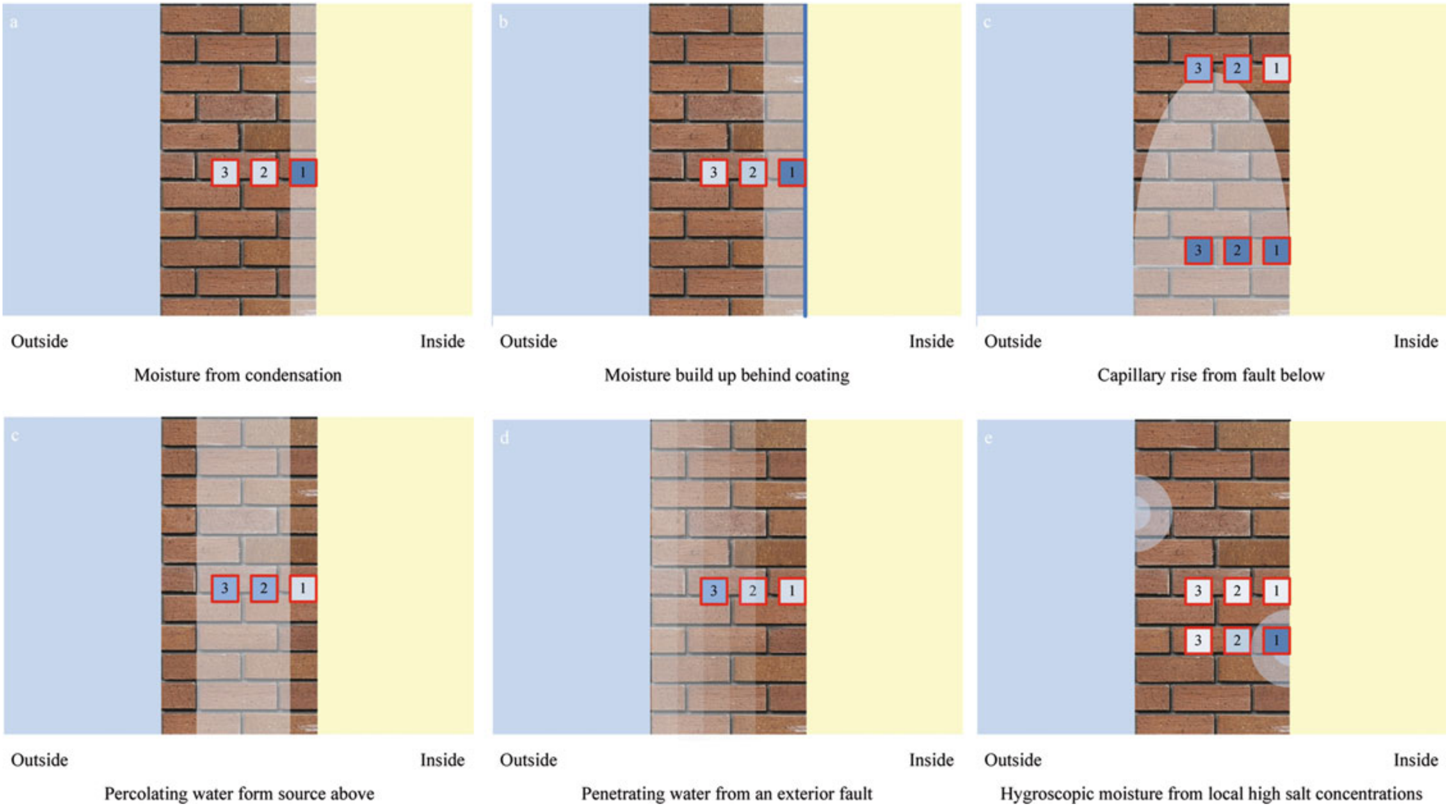
**Fig. 5.6** A typical measurement plan which gives an indication of a typical outlay of drilling positions as well as an interpretation of the results. The black point number 1–12 are the locations the samples are taken. Per locations several squares are presented. Each *square* is divided in two parts: the *upper left triangle* indicates moisture loads, the *lower right triangle* indicates salt loads. The *color* indicates the moisture or salt load: *green*: none, *yellow*: light, *orange*: medium, *red*: high and *purple*: extreme. The number inside the *square* indicates the drilling depth: *1* plaster layer (mixture of powders of several plaster samples), *2* render (mixture of powder of several renders), *3* masonry, drilling depth 0–10 cm, *4* masonry, drilling depth 10–20 cm. Both *3* and *4* can contain brick, mortar or both) (Drawing: Van Rhijn, Rockview)

the soluble ion content of the aqueous extract through ion chromatography (IC) and (inductive coupled plasma) atomic emission spectroscopic techniques.

When the composition of the salt or mixtures of salts is known, the deliquescence point, below which the salt is crystalline, or above which it is in solution, can be determined. In Table 5.4 some deliquescence relative humidities for different pure salts, at different temperatures are provided.

For salt mixtures it is rather difficult to determine a single deliquescence point, Table 5.4 cannot be used since it applies to single salts. Similar mixtures with different ion ratios will have different deliquescence points or transition bandwidths. See Fig. 5.8 for a mixture of sodium nitrate and sodium chloride.

In practice this means that already small changes in the composition of salt mixtures can radically alter the upper and/or lower limits and the size of the transition band width. In these cases it can be difficult to determine the safe region, even if the individual salts have been identified. Also their molar ratios have to be determined in order to calculate the various curves as can be seen in Fig. 5.8. RUNSALT the



Moisture from condensation

Moisture build up behind coating

Capillary rise from fault below

Percolating water form source above

Penetrating water from an exterior fault

Hygroscopic moisture from local high salt concentrations

**Fig. 5.7** A schematic presentation of moisture profiles inside a wall and the possible measurement locations (numbered boxes *1*, *2* and *3*) to determine the moisture content (Source: English Heritage 2014)

**Table 5.4** The deliquescence relative humidity for different salts at different temperatures

| Salt | Deliquescence relative humidity |
|---|---|
| $KNO_3$ | 94.7 % (20 °C, 68 °F), 93.6 % (25 °C, 77 °F) |
| $NH_4NO_3$ | 65 % (20 °C, 68 °F), 61.8 % (25 °C, 77 °F) |
| $Ca(NO_3)_2{\cdot}4H_2O$ | 56.5 % (10 °C, 50 °F), 53.6 % (20 °C, 68 °F), 50.5 % (25 °C, 77 °F) |
| $Mg(NO_3)_2{\cdot}6H_2O$ | 57.4 % (10 °C, 50 °F), 54.5 % (20 °C, 68 °F), 51.4 % (30 °C, 86 °F) |
| $NaNO_3$ | 77.5 % (10 °C, 50 °F), 75.2 % (20 °C, 68 °F), 74.4 % (25 °C, 77 °F) |
| $Na_2SO_4$ | 81,7 % (25 °C, 77 °F) |
| $Na_2SO_4{\cdot}10H_2O$ | 93.6 % (20 °C, 68 °F), 90 % (23 °C, 73 °F), 87 % (25 °C, 77 °F) |
| $MgSO_4{\cdot}7H_2O$ | 90.1 % (20 °C, 68 °F), 94 % (30 °C, 86 °F) |
| $Ca(SO_4){\cdot}2H_2O$ | >99 % RH at 20 °C (68 °F) |
| $CaCl_2{\cdot}6H_2O$ | 33.7 % (10 °C, 50 °F), 30.8 % (20 °C, 68 °F), 22.4 % (30 °C, 86 °F) |
| $MgCl_2{\cdot}6H_2O$ | 33.5 % (10 °C, 50 °F), 33.1 % (20 °C, 68 °F), 32.4 % (30 °C, 86 °F) |
| NaCl | 75.7 % (10 °C, 50 °F), 75.3 % (25 °C, 77 °F) |
| $NH_4Cl$ | 82 % (10 °C, 50 °F), 80 % (20 °C, 68 °F), 77 % (30 °C, 86 °F) |
| KCl | 86.8 % (10 °C, 50 °F), 85.1 % (20 °C, 68 °F), 83.6 % (30 °C, 86 °F) |

Source: Salt wiki: http://www.saltwiki.net/, Greenspan 1977

Note that the deliquescence relative humidity does not change enormously with changing temperature

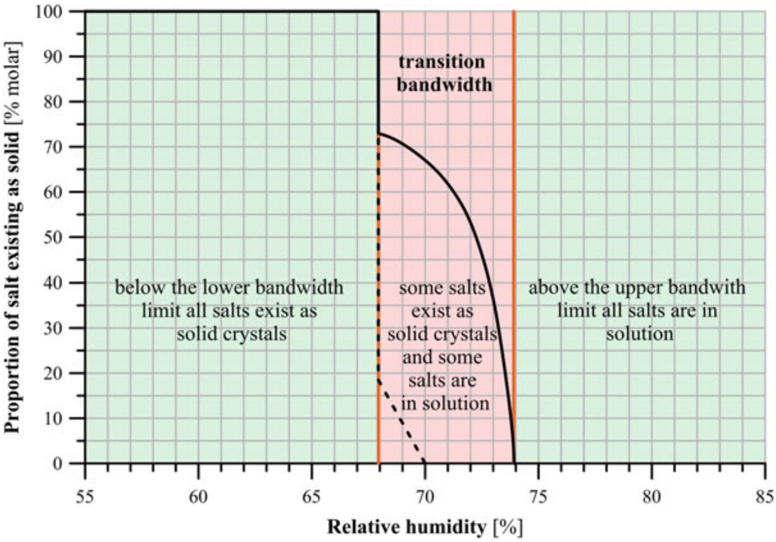


**Fig. 5.8** Representation of the deliquescence point or transition bandwidth for a mixture of salts. The *green* area above the *upper* limit and below the *lower* limit of the transition bandwidth are both safe. At an indoor relative humidity above the *upper* limit all (multiple) salts are in solution and below the *lower* limit all (multiple) salts are crystalized. The *solid line* represents a 1:5 NaNO3: NaCl mixture. The *dashed line* represents a 1:1 NaNO3: NaCl mixture (Source: Price and Brimblecombe 1994)

graphical user interface to the ECOS thermodynamic model for the prediction of the behavior of salt mixtures under changing climate conditions (Price 2000), predicts the crystallization behavior of salt mixtures (see: http://science.sdf-eu.org/runsalt/ for free download). The user is required to provide the concentrations of a range of cations and anions present in the aqueous extract as the input. The program is then able to predict which minerals will exist in the solid state, under specific conditions of relative humidity and temperature.

The risk of salt damage due to an incorrect indoor climate can be summarized by two scenarios:

1. Due to a continuous low indoor relative humidity, the moisture content on the wall surface will be low and crystals will be formed. The rate of drying depends on the local temperature, local relative humidity and air speed. Fast drying is generally more damaging to the surface than slow drying. When the rate of evaporation is larger than the supply rate of the salt solution, evaporation will occur inside the wall with salt accumulation causing *scaling* or *spalling*. This is called crypto-efflorescence;
2. Fluctuations of relative humidity around the deliquescence point or transition bandwidth (Fig. 5.8) will result in a continuous cycle of crystallization and dissolution of salts. This ongoing process will result in damage to the surface, including the pictorial layers.

When moisture evaporates, crystals will grow. The damaging effect of this mechanism is nicely illustrated by the example of sodium sulfate. It is one of the most damaging salts found in buildings. It exists as the anhydrous salt thenardite ($Na_2SO_4$) or as the hydrated salt; decahydrate mirabilite ($Na_2SO_4.10H_2O$) (Espinosa Marzal and Scherer 2008). Thenardite increases in volume by more than three times on conversion to mirabilite. This can lead to high stresses on the pore walls (crystallization pressure) and cause the stone, or its surface layer, to crumble and disintegrate (Price 1996).

It is not easy to mitigate the risk of salts in a building. It requires expertise, very specific knowhow and detailed information about the specific situation in terms of salt (loads and distribution) and moisture (distribution and flow). Since some of these analyses can be very invasive to the building fabric and thus to cultural values, one should be careful to perform a full investigation if the problem is only local. In Fig. 5.9 a roadmap is provided to guide the decisions to sample and/or analyse moisture content and/or salt loads.

Mitigating salt risks is often difficult and expensive. Basically two strategies can be applied: (i) reducing moisture transfer and (ii) reducing salt loads. Replacing salt loaded materials is almost always impossible. Removing salts from the building fabric can be time consuming. Partial salt extraction can be considered. After consolidation, salts can be extracted using a poultice consisting of kaolin, sand and cellulose fibers. More information can be found in Voronina (2011). To prevent the formation of solid salt crystals in or just below the surface, with subsequent damage to the plaster and/or paint layers, it is preferable to keep the salts in one

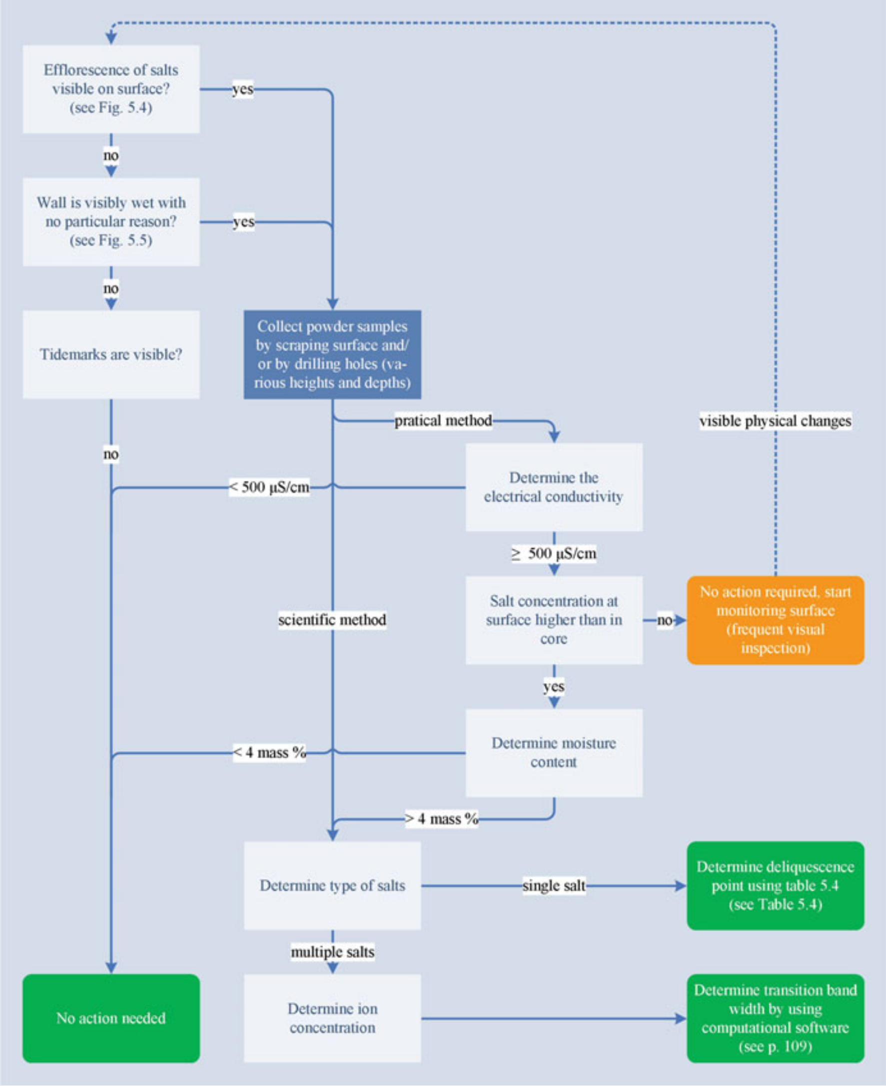


**Fig. 5.9** A roadmap for sampling and analyzing moisture and salt loads

phase. This can either be in solution (i.e. above the upper transition band limit) or as crystals (below the lower transition band limit) (Fig. 5.9, green regions). It should be noted however that some studies indicate that deterioration due to changes of the relative humidity well below the deliquescence point or transition band width still causes severe damage (Nunberg and Charola 2001).

Concluding, mitigating salt risks largely depends on reducing moisture transfer. This can prove to be difficult because some outdoor moisture sources seem more or less infinite, i.e. ground water. Blocking the moisture transport by barriers will reduce the overall transport of salts into the building. Depending on the specific transport mechanism, different blocking strategies are developed. First of all the building itself should be designed to prevent ingress of rainwater. Since ground water is the most problematic source the capillary uptake of water has to limited Traditionally this was done by using a dense brick and trass grout. In cases where this was ineffective, a barrier was made using different methods. Mechanical barriers were created by pressing lead or glass sheeting into the wall respectively. Chemical barriers were implemented by injection. Some of those methods are effective. Chemical injection seemed to be ineffective for a long time. To prevent (driving rain) water penetrating into the building in the seventies, buildings facades were treated with a moisture barrier coating. This strategy had huge side effects. The coating drastically altered the surface of the building, with subsequent loss of cultural value. Since this coating was hardly ever fully blocking moisture transport, water could accumulate inside the wall. Evaporation was impossible and the moisture load of the wall increased. When outdoor temperatures dropped below freezing point, frost damage occurred. But research showed injection can be effective in masonry if the monomers can fully polymerize (van Hees et al. 2011). So in the beginning the injection was working slowly, but as the structure became drier the efficiency increased, but only after a decade.

## 5.4 Frost Damage

In countries with cold climates, buildings are exposed to cycles of freezing and thawing. Problems related to freeze-thaw attack of building materials such as stone and concrete, arise when unbound water in the pores freezes. When water freezes it expands by around 9 %. This causes crystallization pressure within the material's pore structure. As the material reaches its saturation point, and over many cycles of freezing and thawing, this pressure causes tensile forces to build up in the material's matrix. If these forces exceed the internal tensile strength, it will cause deterioration by way of general disruption, cracking, scaling, or pop outs, leaving it exposed to further attack and ultimately failure. Fired brick is somewhat less susceptible due to the fact that the external surface of the brick is more water repellent. However, when damage to the outside layer has already occurred, water uptake is easier and the risk of frost damage increases. This issue has particular relevance for energy efficiency retrofits, because the addition of interior insulation causes the masonry to become colder and thereby reducing the drying potential. Moisture will accumulate inside the wall over time (Fig. 5.10).

**Fig. 5.10** Typical example of frost damage of brick masonry with a hard cement jointing and a relatively soft brick

## 5.5 Corrosion of Metals

Many different metals can be found in historic buildings. They are used for all kinds of applications ranging from structural to decorative elements, from trusses to support the roof, to Art Nouveau lock plates. Most commonly found metals in historic houses are susceptible to relative humidity and temperature. In Sect. 4.2.1 some aspects of corrosion are discussed. The indoor corrosion rates are significantly lower than the rates outdoors. The synergy between the chloride deposition rate, with the time of rainfall and the time of wetness, are considered to be the most significant variables influencing corrosion rates. Especially in humid-tropical marine environments corrosion rates can be very high. In the northern hemisphere examples of corrosion induced structural damage can be found in e.g. nineteenth century greenhouses, where very aggressive tropical indoor climate conditions inflicted heavy corrosion damage to the iron frames (Lauriks et al. 2008).

In severe complex cases corrosion monitoring may be useful. As it is difficult to anticipate the influence of numerous variables that could lead to corrosion problems, such as: humidity, temperature, light, historical exposure to corrosive environments (surface contamination), historical surface/preservation treatments, materials of construction and their historical processing, etc.. Several techniques are available to assess corrosion rates in situ. The corrosion rate depends on:

- The ambient conditions. High temperatures, high relative humidities or water, and the availability of oxygen will lead to higher corrosion rates;
- Type of metal. Some metals like copper are noble and therefore have a high resistance to galvanic corrosion than the less noble metals, like aluminum or zinc;

- Pollutants. Some atmospheric pollutants will react with water and oxygen to form acids. Acids increase the cathodic reaction. Sulphates and chlorides are the most effective corrosion agents. Water is an important precondition. In the absence of water most contaminants would have little or no effect. The presence of salts at the surface absorbs ambient moisture. The surface becomes wetter at lower relative humidity, making corrosion possible. Salts also increase the electrolytic effect.

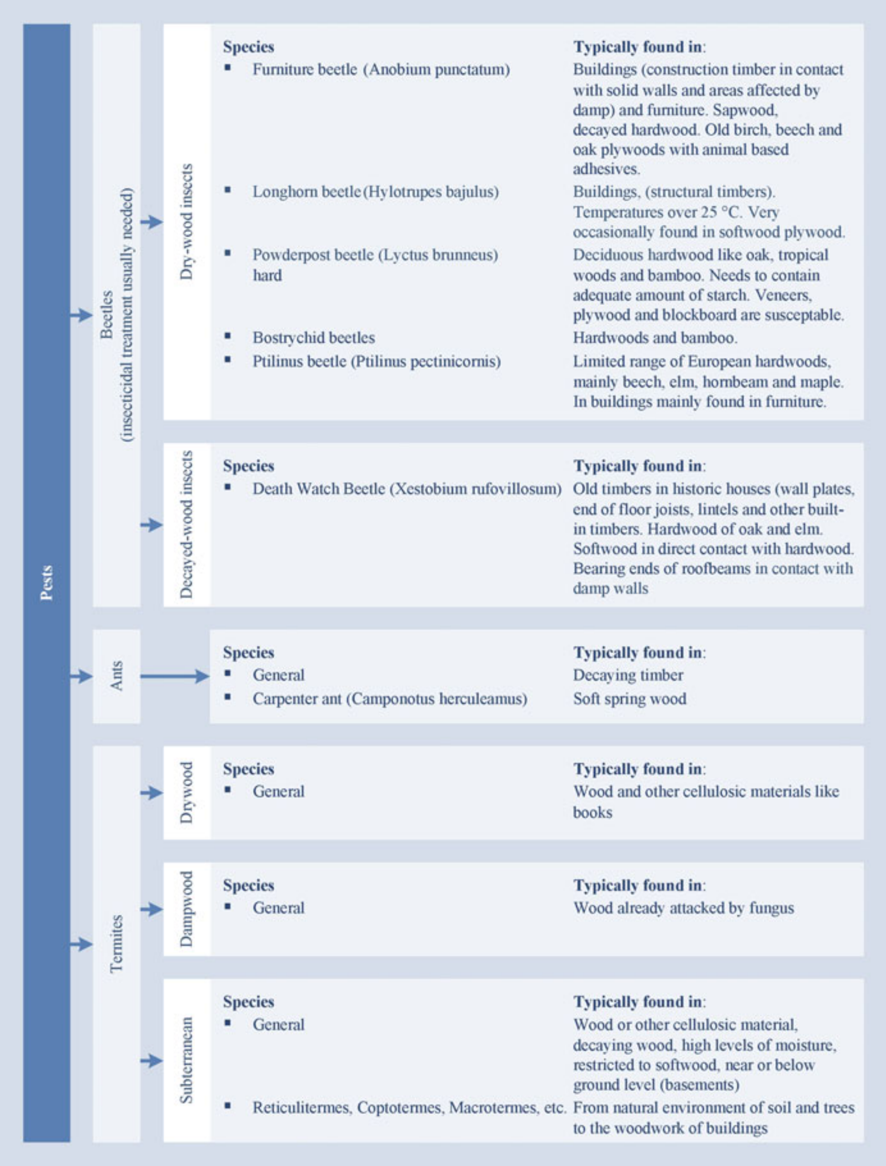
Generally the conclusion is that (very) high relative humidities should be avoided, since metals show an exponential increase in decay (corrosion) rate with increasing relative humidities above 65 %.

## 5.6 Wood Deterioration by Insects in Buildings

There are many insects species that can be observed inside buildings, not all of them are capable of damaging the building. Some, mainly beetles (Coleoptera) and termites (Isoptera), can cause serious damage to the building fabric. Especially wooden finishes are generally at risk. The risk of insects damage is primarily determined by the wood characteristics, such as species, age, the availability of sapwood and the amount of certain nutrients. The indoor climate has only a very limited influence on the risk. Although the wood moisture content plays a role in the susceptibility of the wood for insect attack. In Fig. 5.11 a short overview of the most common wood damaging insects for Northern Europe and the US are presented.

Insects can be divided into (i) damp (green)-wood insects (ii) decayed wood insects and (iii) dry-wood pests (Fig. 5.11). Dry-wood insects live in wood with a moisture content of less than 20 %, which is free of fungal decay. Damp-wood insects attack either living trees or freshly felled logs, or wood with fungal attack. Like fungi, pests require a certain temperature and relative humidity range and a certain moisture content of the wood to successfully multiply and grow. Insects are unable to regulate their own temperature. Body functions and hence development and reproduction rates are more rapid at higher temperatures (>25 °C (>77 °F)). At lower temperatures these rates are reduced, or even stop. Slow breeding occurs at temperatures between 15 and 20 °C (59–68 °F) and breeding stops at temperatures below 10 °C (50 °F) (Pinniger 1994). This means that the best way to control pest infestations is to ensure that the temperature inside the wooden structure is kept as low as possible.

Insects require some moisture to grow and multiply. Some species like silverfish need high relative humidity. Others can obtain water from the conversion of foodstuffs. For most species the optimum relative humidity varies between 80 and 90 %. Below 50–60 % ambient relative humidity growth is nearly impossible, but there are exceptions like the brown powder post beetle (*Lyctus brunneus*), which will survive at relative humidities as low as 30 %. Some species will spread faster in conjunction with fungal attack. For those species the fungus is probably needed to soften the hardwood and thereby making it easier to attack. The death watch beetle for instance needs the presence of fungal decay – active or old – before



| Pests | Group | Type | Species | Typically found in: |
|---|---|---|---|---|
| Pests | Beetles (insecticidal treatment usually needed) | Dry-wood insects | Furniture beetle (Anobium punctatum) | Buildings (construction timber in contact with solid walls and areas affected by damp) and furniture. Sapwood, decayed hardwood. Old birch, beech and oak plywoods with animal based adhesives. |
| | | | Longhorn beetle (Hylotrupes bajulus) | Buildings, (structural timbers). Temperatures over 25 °C. Very occasionally found in softwood plywood. |
| | | | Powderpost beetle (Lyctus brunneus) hard | Deciduous hardwood like oak, tropical woods and bamboo. Needs to contain adequate amount of starch. Veneers, plywood and blockboard are susceptable. |
| | | | Bostrychid beetles | Hardwoods and bamboo. |
| | | | Ptilinus beetle (Ptilinus pectinicornis) | Limited range of European hardwoods, mainly beech, elm, hornbeam and maple. In buildings mainly found in furniture. |
| | | Decayed-wood insects | Death Watch Beetle (Xestobium rufovillosum) | Old timbers in historic houses (wall plates, end of floor joists, lintels and other built-in timbers. Hardwood of oak and elm. Softwood in direct contact with hardwood. Bearing ends of roofbeams in contact with damp walls |
| | Ants | | General | Decaying timber |
| | | | Carpenter ant (Camponotus herculeamus) | Soft spring wood |
| | Termites | Drywood | General | Wood and other cellulosic materials like books |
| | | Dampwood | General | Wood already attacked by fungus |
| | | Subterranean | General | Wood or other cellulosic material, decaying wood, high levels of moisture, restricted to softwood, near or below ground level (basements) |
| | | | Reticulitermes, Coptotermes, Macrotermes, etc. | From natural environment of soil and trees to the woodwork of buildings |

**Fig. 5.11** A short list of the most common pests for Northern Europe and the US

they can attack oak (Ridout 1999). For some larvae species the temperature ranges and wood moisture content requirements are given in Table 5.5.

As can be seen from this table the requirements for growth for larvae varies. The minimal to optimal temperatures at which larvae for the three beetles in Table 5.5 can grow, all fall within the range found in museums.

**Table 5.5** Temperature and wood moisture requirements of the larvae of some wood destroying beetles (Unger et al. 2001)

| | Temperature [°C (°F)] | | | | Wood moisture content [%] | | |
|---|---|---|---|---|---|---|---|
| Species | Min. | Optimum | Max. | Lethal | Min. | Optimum | Max. |
| Common furniture beetle (*Anobium punctatum*) | 12 (54) | 21–24 (70–75) | 29 (84) | 47–50 (117–122) | 10–12 | 28–30 | 47–50 |
| House longhorn beetle (*Hylotrupes bajulus*) | 16–19 (61–66) | 28–30 (82–86) | 35 (95) | 55–57 (131–135) | 9–10 | 30–40 | 65–80 |
| Lyctus powderpost beetle (*Lyctus brunneus*) | 18 (66) | 26–27 (79–81) | 30 (86) | 49–65 (120–149) | 7–8 | 14–16 | 23 |

The risk of insects cannot significantly be reduced by controlling the humidity to a specific level. Having developed the ability to extract, replenish, and harbour water carefully, insects can support their mobile lives. In order to prevent pest infestation a proper integrated pest management (IPM) should be implemented in the museum. Integrated pest management comprises five logically consecutive steps: avoid, block, detect, confine, and treat. The emphasis lies on preventive measures and their monitoring. Control measures are taken only in the last instance (Brokerhof et al. 2007). An assessment of the kind and extent of insect attack, possible causes and changing environmental conditions always precede remedial treatment or eradication measures. Toxic substances are only used when strictly necessary and in least possible amounts. Such an integrated approach to pest management consists of the following five steps:

1. What kind of insect pest is it, where is it, what is the current insect activity (is it alive or not) and is there any structural damage;
2. Assess what environmental conditions are allowing the pest to thrive in case of more serious damage with large numbers of insects;
3. Alteration to unfavorable environmental conditions for the pest or – in case of small numbers of insects – monitoring of the insect attack;
4. Assess if remedial treatment is more beneficial than environmental control alone.
5. Selecting a remedial treatment with the least use of toxic biocides

Controlling the indoor climate to reduce the risk of pest infestations is not realistic. To a certain extent the extent of the infestation can be influenced by controlling the moisture content of building timbers and prevent large amounts of moisture to build up in the timbers. Maintenance and good design are key factors. Only with an average wood moisture content below 12 % throughout the year, is the risk significantly reduced. In practice this is hardly ever achievable. A more realistic approach is to control the average wood moisture content below 15 %. This will prevent serious wood deterioration in most cases.

## 5.7 Decorative Finishes

Many historic houses contain highly appreciated immovable decorative layers that are susceptible to an incorrect indoor climate. These include wallpaper, painted wall hangings, gilt leather, wood paneling and painted ceilings and many other constructions and materials. Since all these materials and constructions react differently to an incorrect indoor climate it is impossible to find one optimum to reduce the climate risk to zero. Some climate risk will always have to be accepted.

The materials used to decorate houses are generally more robust than their moveable counter parts. For example the climate risks to wallpaper is to some extent similar to works on paper; it will be equally susceptible to chemical degradation due to temperature. But glued to a wall, the wallpaper might be more susceptible to relative humidity fluctuations when compared to the this risk for works on paper. The thickness of the wallpaper layering will give it more strength to withstand stresses than single sheets of paper will have. And painted ceilings or wood paneling will behave the same as panel paintings. But the thicker planks of the ceiling will give it a longer hygric half- life and thus a lower risk from relative humidity fluctuations. Another issue is that the loss of value associated to a shrunken wood panel or cracked ceiling is generally lower than a similar change on a panel painting.

The durability of collections, immovable and moveable is nicely illustrated by the preservation environment in Skokloster, Sweden. The castle is often quoted as an example of a complex interior with a wide variety of finishes and a large amount of moveable objects in an uncontrolled environment. Over the years several inventories of the collection have been made and the overall degradation rate over these 350 years is considered to be very low, while the castle lacks every form of climate control. Indoor temperatures in winter drop to as low as −10 °C (14 °F) in winter. Sometimes the relative humidity rises to almost 90 %. The exposure time is however short enough to keep mold growth under control. Even though the air exchange rate of the building can cause temperature and relative humidity fluctuations, these are buffered by the heavy brick building and its interior finishes and collection. The low indoor temperatures will also reduce the moisture transport in and out of hygroscopic materials as a result of an increased relative humidity. Both the large thermal mass and the low indoor air temperature results in slow changes of the moisture content of the organic materials inside (Holmberg et al. 2006).

As already mentioned above, immovable collections are generally less susceptible to an incorrect indoor climate than their moveable counter parts. But in some cases immovable collections can exist of (very) susceptible objects, materials and/or constructions, which also require a specific indoor climate for their long term preservation. To assess these climate risks for decorative finishes it is essential to understand the specific construction, mounting and (chemical) composition of the objects in situ, with special attention to the (microscopic) changes that might occur over time. To fully understand the climate induced material changes, sometimes material technical analysis is required. An example of this, is the study of an late eighteenth century wall-painted imitation relief located in the so-called Hofkeshuis in the Netherlands (Keune et al. 2015). The wall painting, covering three walls was made in 1778. During it's life the painting has continuously, but partly, been exposed to direct sun light. To understand the effect of the indoor climate and direct sun light, the concentration of lead soaps in the paint and the craquelure patterns were studied in detail. This information can then be used to design a natural lighting protocol and think about the (non)sense of climate control.

In Chap. 4 the impact of an incorrect climate on different materials is discussed in great detail. Here only gilt leather and wallpaper will be discussed.

### *5.7.1 Gilt Leather*

Traditional gilt leather is generally composed of a piece of leather which is covered with a thin layer of egg-white or fish-glue to hold a metal leaf, generally silver. The pores of the silver leaf are then filled by polishing with a coating layer of gelatin, egg-white or fish glue. The surface is subsequently covered by a varnish layer, that can be painted over and again covered by a second protective varnish layer (De Keijzer and Koldeweij 2007). The sheets or strips of gilt leather were sewn together with rope. Gilt leather can be found in historic houses. The laminate of different layers with potentially different responses to relative humidity fluctuations is of great concern to those who are responsible for it. Although many deformations, cracking and material loss are regularly observed, not much research has been done on the subject of climate risks to gilt leather.

The susceptibility of gilt leather is illustrated by the observations made in a conservation project of the gilt leather wall hangings that upholster the walls of its Veronese Room Gallery in the Isabella Stewart Gardner Museum. It is observed that humidity-induced movement of the leather was visibly causing stress in the artefacts. They were buckling and pulling away from the nails which attached them to the walls. The mass change of gilt leather as function of relative humidity, is roughly linear with a hygric half-life for full response of an historic piece of gilt leather in the order of magnitude of 1–2 h (Talland et al. 2007; Julian 2014). So relative humidity fluctuations with a duration of 3–6 h will be fully experienced by the gilt leather. It is unclear what the maximum acceptable relative humidity fluctuation might be to keep stress levels below yield point.

Gilt leather becomes more flexible at higher relative humidity. As a result, it is generally preferred to secure a constant high relative humidity level of around 60 % (Adamowicz and Kozłowski 2007). Which is often not an easily reached relative humidity in the historic buildings visited by a large number of people and will most likely result in significant risks to other parts of the building.

### *5.7.2 Traditional Wallpaper*

Early wallpaper was handmade and consisted of small sheets of rag paper printed by wood blocks. In the 18th century these single sheets were glued together to form a length to print on. The paper was distempered to allow printing, using chalk and glue size. By the mid-nineteenth century cheaper wallpaper could be produced using wood pulp. Printing with design in relief could be done by new types of binding media such as starches, gum and casein, also newly developed synthetic pigments were applied (National Trust 2011).

The finished wallpaper was glued onto a stretched canvas using warm animal glue. The cavity between the wall and canvas prevented direct contact between the wallpaper and the (cold) outside wall. Many wallpapers however, were stuck or nailed directly onto the plaster or wooden paneling on the wall. There was a great variety of wallpaper quality from watermarked handmade, to cheap paper. Flour paste was used to hang the wallpaper.

The organic nature of the wallpaper makes it susceptible to an incorrect relative humidity. If wallpaper hangings become too dry, the risk of mechanical damage increases dramatically. The wallpaper will become brittle and the adhesive might fail, the wallpaper might delaminate and paint might flake off. Obviously when the relative humidity is too high, for too long, the risk of mold is significant. Especially when the wallpaper is close to an uninsulated outside wall that might become damp at lower temperatures. In moist conditions the wallpaper will lose its strength and the risk of delamination and paint flaking is significant.

Safe relative humidity specifications depend on the specific material characteristics of the wallpaper. The preservation of wallpaper is most effectively realized by maintaining a low temperature to reduce chemical processes, and a set point for relative humidity around 40–45 %, to optimize both the risk of chemical damage, which will benefit from a very low relative humidity and mechanical damage, which will benefit from a relative humidity between 40 % and 65 % ±5 % (see Sect. 4.2).

## 5.8 A Case Study

Museum Our Lord in the Attic in Amsterdam is located in an early seventeenth century canal house. The museum consists of several authentic period rooms, and has an original seventeenth century clandestine church as its absolute highlight. The building, including the hidden church, has been functioning as a museum since 1888. It is a very important Dutch monument because of the authenticity of the rooms and spaces. The mission of the museum is ‘to keep the cultural and religious heritage of Catholic Amsterdam alive’. This means that the church is still used for services and events such as weddings. The museum has been receiving an increasingly large number of visitors – approximately 93,000 in 2014.

Users and visitors have more and more, a problem with the museum indoor climate: it is often too hot in the summer, while during the winter it feels to dry. Because panel paintings have cracked in the past during cold winter months, movable humidifiers and dehumidifiers have been placed in different locations inside the museum. In practice, these locations proved to be rather fixed.

The climate inside the building has been measured for a period of 1 year (Maekawa et al. 2007) (see Fig. 5.12). During this period the relative humidity inside the church stayed between 40 % and 80 %, and the temperature (T) between 11 °C (52 °F) and 29 °C (84 °F). The low temperature occurred as a result of failure of the heating system. If we disregard a few brief extreme fluctuations, which are not ‘felt’ by the objects, then the museum climate stays within the range of $45\ \% < \mathrm{RH} < 70\ \%$ and $17\ ^\circ\mathrm{C} < T < 26\ ^\circ\mathrm{C}$ ($63\ ^\circ\mathrm{F} < T < 79\ ^\circ\mathrm{F}$). This is also referred to as an ASHRAE climate class C and is reasonably close to a B-climate, corresponding to the expectations for an uninsulated historic building, i.e. building class 3 (ASHRAE 2011).

During the heating season a significant amount of moisture is introduced inside the building, and because the windows are single-glazed, condensation takes place continuously. The consequences of this surface condensation are particularly visible on the wooden window frames that rapidly rot. As condensation on windows is often an indication of problems elsewhere in the building envelope, some of the beam heads in the building showed extensive rot upon inspection and had to be impregnated by epoxy. A thermal image of the interior face of a wall in the church is presented in Fig. 5.13. It clearly shows that part of it corresponds to a cold outer wall (blue color: $13\ ^\circ\mathrm{C} < T < 15\ ^\circ\mathrm{C}$, $55\ ^\circ\mathrm{F} < T < 59\ ^\circ\mathrm{F}$), and that the remaining part on the left is a partition wall between two houses (red color: $17\ ^\circ\mathrm{C} < T < 19\ ^\circ\mathrm{C}$, $63\ ^\circ\mathrm{F} < T < 62\ ^\circ\mathrm{F}$). The indoor relative humidity in the vicinity of the cold outer wall will be significantly higher, up to 70 %, than elsewhere in the room. Because of thermal shielding by the panel painting even higher relative humidity levels can be expected behind the painting.

Increasing the insulation and reducing the natural ventilation in such a building would require an exceedingly drastic intervention. Improving the indoor climate conditions in the building is therefore hardly possible without detracting from the experience value of the monument. It was decided that in winter time temperature maximum set points were adjusted to 17 °C (63 °F) and 40 % relative humidity. Since then condensation is very rarely observed on the windows. During hot summer days large fans are placed in church and visitors are given hand held fans to provide some human comfort.

## 5.9 Conclusions

It is clear that (historic) buildings will suffer from other causes than an incorrect indoor climate. In massive masonry or concrete buildings sometimes cracks may run from the outside to the inside due to subsidence. Through these cracks rainwater

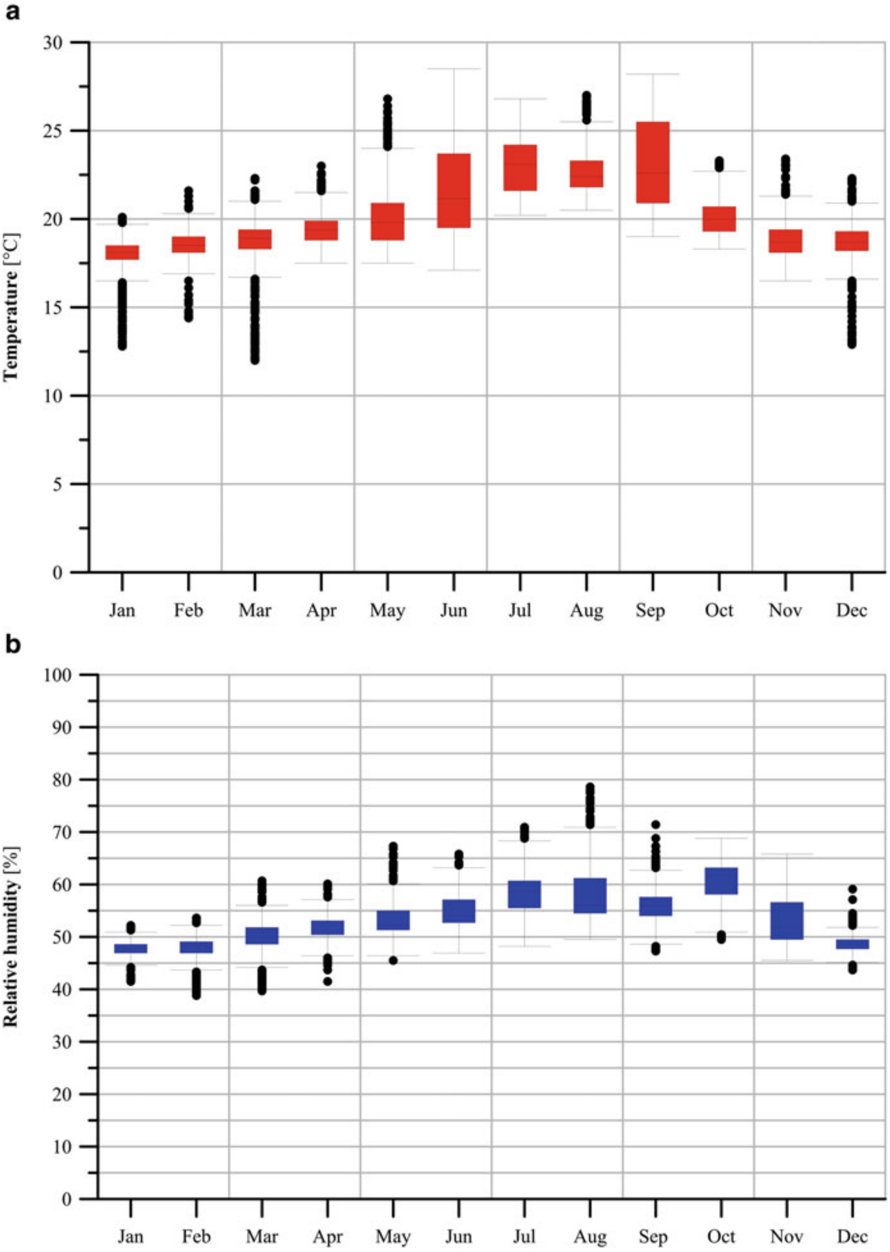


**Fig. 5.12** Climate data from 2005 in the Our Lord in the Attic (Ons' Lieve Heer op Solder) church, presented as box plots. (**a**) Represents the measured temperature, (**b**) represents the measured relative humidity. The height of the boxes indicates the relative humidity range within which 50 % of the data points are, and the *horizontal lines* below and above the box indicate the relative humidity range corresponding to 80 % of the data points. The black dots represent the outliers

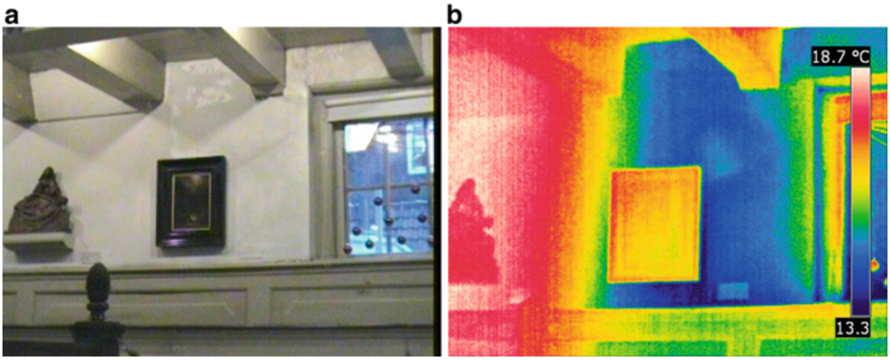


**Fig. 5.13** Interior face of a wall in the Our Lord in the Attic (Ons' Lieve Heer op Solder) church (**a**). Thermal image of the same place taken from the same position (**b**) (Photos: Neuhaus, Eindhoven University of Technology)

**Fig. 5.14** Stalactites made of salts due to water entry through cracks in the bunker complex at the Obersalzberg, Germany

can easily penetrate into the building. Liquid water will flow from the outside to the inside, carrying dissolved salts. When water evaporates crystals are formed, if the process continues for prolonged periods of time (decades) even stalactites or stalagmites can be produced (Fig. 5.14).

Maintenance of the building fabric is key. Structural stability, keeping the building wind- and watertight and proper rainwater management is of upmost importance. But if this is in order the building fabric and its interior finishes can still suffer from an incorrect indoor climate. Similar to moveable collections, there

**Table 5.6** Climate specification for building and their susceptibility to the wrong indoor climate

| | Temperature | | Relative humidity | |
|---|---|---|---|---|
| | Lower limit | Upper limit | Lower limit | Upper limit |
| Fungal attack (organic materials like wood, wallpaper etc.) | 0–5 °C (32–41 °F) | 28 | – | Below 60 % for no decay, above 60 % time dependent |
| Pest infestations (organic materials like wood, wallpaper etc.) | 12 °C (53.6 °F) | 29 | – | Below 60 % for no infestation[d] |
| Salt attack (mainly brick and natural stone) | – | – | As high as possible not exceeding the upper limit[c] | Lower limit transition band width[c] |
| Frost damage (mainly brick and natural stone) | 0 °C (32 °F)[a] | – | – | – |
| Thermal expansion (mainly natural stone, metals in masonry or combinations of brick and concrete) | –[b] | –[b] | – | – |
| Corrosion (metals) | – | As low as possible | – | 60 % or as low as possible |
| Building as a whole | 0 °C (32 °F) | Depending on the problem to avoid | As high as possible not exceeding the upper limit | 60 % |

[a] A temperature of 5 °C (41 °F) or higher is often cited in literature as safe limit to prevent frost damage

[b] Cracks due to thermal expansion primarily depend on outdoor temperatures and solar radiation

[c] Depending on salt or salt mixture. The aim is to have the salt or salt mixture in either a fully dissolved or fully crystalized state. This means that in a dry environment we do not want the local relative humidity to exceed the lower limit of the transition band width. In a moist environment we do not want the relative humidity to drop below the upper limit of the transition band width. In Fig. 5.8 for example we would like our ambient relative humidity in the green areas as close as possible to the red area

[d] Controlling moisture content is a better way to control decay

is not one safe indoor climate. The indoor relative humidity can be too high, too low or too fluctuating, while the temperature can be too low or too high. For (historic) buildings a suitable indoor climate is summarized in Table 5.6. Moisture is the largest risk to the building fabric. If moisture can accumulate, the risk of rot and mold are significant. At very low temperatures the risk of freezing and condensation increases.

The result of this step is an overview of the building materials indicating which of these materials are susceptible to which aspect of the indoor climate. The specific temperature and relative humidity set points and acceptable fluctuations can be developed and specified for the different seasons.

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# Chapter 6
# Step 5: Assessing Human Comfort Needs

**Abstract** Thermal comfort is a judgment involving different inputs influenced by physical, physiological, psychological and other processes. In this chapter these aspects are discussed in more detail. Acceptable ranges of operative temperature and humidity for a typical museum indoor environment are provided. The relationship between skin temperature and Predicted Mean Vote (PMV) shows that humans are much more sensitive to warm conditions than to cool conditions.

A new approach in thermal comfort studies is to take into account the physiological feedback (acclimatization) and psychological feedback (habituation and expectation). This approach is used to develop an adaptive model. With changing outdoor temperature, people automatically change their clothing and therefore their preferred indoor comfort temperature changes.

The volume of fresh air that needs to be supplied (ventilation) can generally be kept very small for collection preservation. For human health, ventilation is important and regulated in law. In public areas, the volume of fresh air that needs to be supplied can be adjusted according to the expected number of visitors. This chapter will show how these varying factors can be understood and balanced within a museum setting.

**Keywords** Thermal comfort • Predicted mean vote • Predicted percentage dissatisfied • Adaptive comfort model • Indoor air quality

## 6.1 Introduction

Satisfaction with the thermal environment is important because it influences health and productivity of people. The negative effects on health and performance that occur, especially when people feel warm at raised temperatures, are caused by physiological mechanisms and can lead to sick building syndrome symptoms.

The temperature set point for the museum indoor environment is predominantly based on the needs of the visitors and staff, much less on the needs for the collection. Generally collection preservation increases with lower temperatures, while humans prefer relatively high temperatures (19 °C$<T_{\text{preferred}}<$ 26 °C: 66 °F $< T_{\text{preferred}} <$ 79 °F). This could allow for a different temperature regime during closed periods. During closed hours there is no need for thermal comfort, and

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consequently the temperature set point can then solely be based on the collection requirements. Especially in countries where heating is required for thermal comfort, a night time temperature set back could increase collection preservation, especially of chemically unstable materials and decrease energy consumption.

## 6.2 Parameters Influencing Thermal Comfort

People are sensitive to temperature, but significantly less sensitive to relative humidity, to ensure human comfort control over temperature is most important. Thermal comfort is defined in different ways. In ASHRAE (2009) thermal comfort is defined as ‘that expression of mind which expresses satisfaction with the thermal environment’.

Thermal comfort can be divided into whole body comfort and local thermal comfort (comfort or discomfort to specific areas of the body). It depends on four environmental and two personal factors:

- Air temperature,
- Mean radiant temperature,
- Air velocity,
- Relative humidity,
- Clothing insulation
- Activity level (metabolic rate)

The air temperature expresses the average temperature of the air surrounding the occupant. The mean radiant temperature is related to the amount of radiated heat/cold transferred from a surface, this depends on the surface temperature and the material’s ability to absorb or emit heat. Heat is absorbed from, or released to, the surroundings through convection and conduction (heat transfer between our skin and the air), radiation (between our skin and clothing surfaces and surrounding building surfaces), and transpiration. The greater the temperature difference, the more heat is absorbed or released by the skin.

The air velocity influences the transfer of heat; a high air velocity increases the heat transfer, which results in a cooling effect. Low relative humidity will also increase the rate of heat transfer, but this effect is negligible in the RH range 30–70 %.

The amount of thermal insulation, i.e. thickness of clothing, worn by a person has a substantial impact on thermal comfort, because it influences the heat loss and thereby the thermal balance. Layers of insulating clothing prevent heat loss and can either help keep a person warm or lead to overheating. The values vary from 0.5 clo for clothing worn in tropical countries and during summer in the Northern hemisphere to 1.0 clo for winter clothing.

The activity type and level will determine the metabolic rate and thereby the amount of heat produced, this is expressed by the so-called met value. Low activity has a low met value and more activity increases the met value. Some common

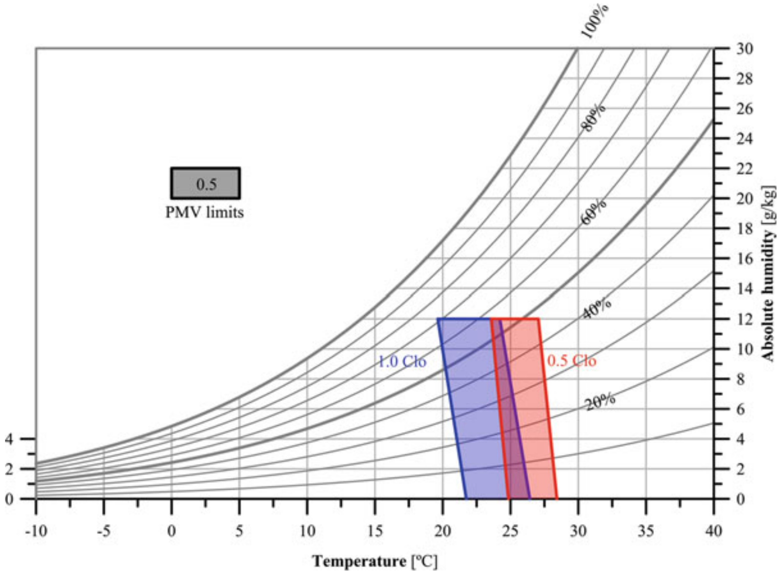

**Fig. 6.1** ASHRAE summer and winter comfort zones. Acceptable ranges of operative temperature and humidity with air speed ≤ 0.2 m/s for people wearing 1.0 and 0.5 clo clothing during primarily sedentary activity (≤1.1 met) (ASHRAE 2009)

values are 0.7 met for sleeping, 1.0 met for a seated and quiet position, 1.2–1.4 met for light activities standing, 2.0 met or more for activities that involve movement, walking, lifting heavy loads or operating machinery. In a museum the metabolic rates are typically 1.2–1.7 met.

Figure 6.1 shows the typical comfort zones for summer and winter conditions for a museum, with an air speed lower or equal to 0.2 m/s, visitors and staff wearing winter (1.0 clo) and summer clothing (0.5 clo) during primarily sedentary activity (≤1.1 met). This explains why gallery staff who sit and watch visitors might feel cold whereas the visitors don't. It is due to different clothing and activity levels, i.e. visitors often keep their coats on as they walk round, while the member of staff with uniform (sometimes without a coat) sits still and watches. The operative temperature is a weighted average of the air and surface temperatures.

## 6.3 Fanger's PMV Model

In 1970 Fanger developed an empirical model that was capable of predicting the overall (whole-body) thermal comfort for a group of occupants. This model was based on regression equations, which were derived from subjective responses. This method is used to determine the optimum temperature conditions, to satisfy the largest possible percentage, of a given group of occupants. It was assumed that a

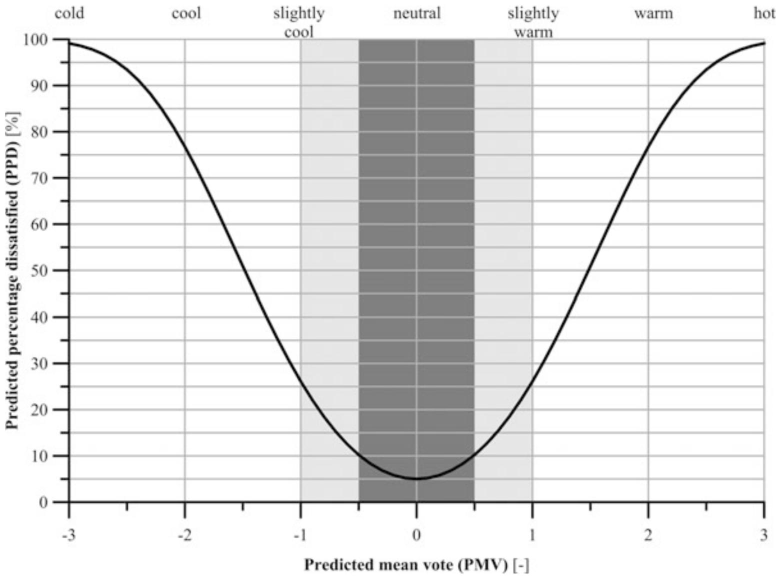

**Fig. 6.2** Predicted Percentage of Dissatisfied (PPD) as function of Predicted Mean Vote (PMV) (Fanger 1970)

person will experience the most comfortable condition in a thermal neutral condition. A thermal neutral condition was defined as the condition wherein a person does not prefer either a colder or warmer environment. This model is known as the Predicted Mean Vote (PMV) model, which predicts the mean thermal sensation, and the percentage of people that will be dissatisfied due to the thermal environment (PPD: Predicted Percentage Dissatisfied). Results of the model are expressed on a seven-point comfort scale from too cold to too hot. Zero means that most people are satisfied with the thermal climate, the negative scale depicts a discomfort due to being too cold and the positive scale for being too warm (ASHRAE 2009).

In Fig. 6.2 the percentage of dissatisfied people (PPD) is presented as function of the PMV. Notice that even a PMV of zero yields 5 % of dissatisfied people, indicating that it is impossible to make everyone in a group feel thermally comfortable.

To understand why people become uncomfortable at certain temperatures, the relationship between skin temperature and Predicted Mean Vote (PMV) was studied in greater detail. Figure 6.3 shows the mean skin temperature as a function of the PMV. The green zone shows the people that are thermally neutral ($-0.5 < \text{PMV} < 0.5$), purple shows the PMV of people being too cold ($-3 < \text{PM} < -0.5$) and red indicates too warm ($0.5 < \text{PMV} < 3$). The line in the graph shows that the skin temperature can decrease from 34 °C (93 °F) to 27.5 °C (82 °F) to reach a PMV of -3 (people are too cold), while already a 1 °C (2 °F) raise of skin temperature gives a PMV of +3 (people are too warm). Indicating that humans are much more sensitive to warm conditions than to cool conditions: the human thermoregulatory system

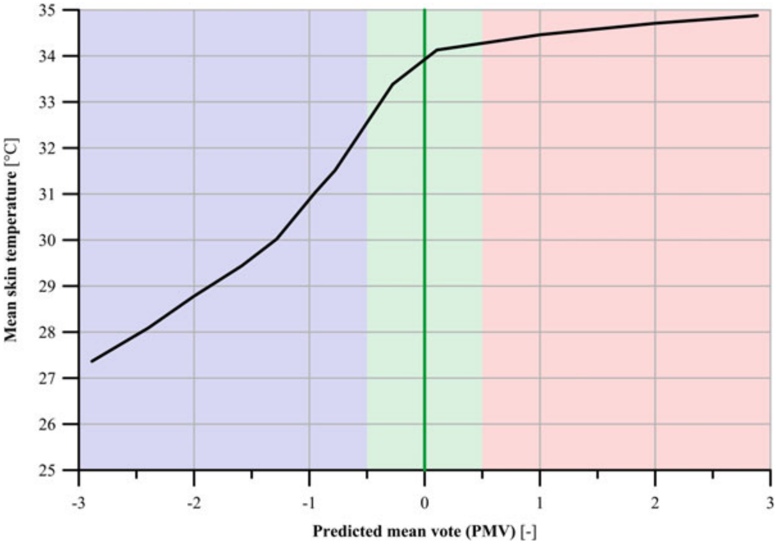

**Fig. 6.3** Mean skin temperature as a function of Predicted Mean Vote (PMV). The results are obtained from a thermo-physiological simulation using the virtual thermoregulation model Fiala-FE (Paulke 2007) over the whole PMV range

handles cold situations more effectively than warm situations. Generally cold conditions occur when outdoor temperatures are low and people are generally dressed with more insulating clothing. Cold environments in a warm outdoor climate, such as caves and tombs are generally regarded as pleasant. But unconditioned historical buildings that are very hot in summer (or year round in the tropics) are generally a challenge, although discomfort can be somewhat reduced by warning the visitors in advance.

The PMV model is now the most common model used in building practice to predict thermal comfort during the design process of a building under uniform and steady-state environmental conditions. This method treats all occupants the same and disregards location and adaptation to the thermal environment. It basically states that the indoor temperature should not change as the seasons do. Rather, there should be one set temperature year-round. This is taking a more passive stand that humans do not have to adapt to different temperatures since it will always be constant. The PMV model is designed for buildings with uniform and steady state conditions but might not apply for environments that are thermally much less stable, such as churches and historic houses.

The PMV model is often used to evaluate discomfort in an existing situation, but the question is if the static model can satisfactorily be used to evaluate dynamic real life situations. In museum galleries for example visitors generally have relative short dwelling times. Given the fact that the human body needs at least 30 min to acclimatize to an environment, some thermal discomfort in specific galleries could be possible. Here psychology plays an important role. When visitors are aware of the fact that the environmental conditions are uncomfortable, i.e. designed for the conservation of the collection, they will have fewer expectations regarding their personal comfort and less quickly feel uncomfortable. Museum staff would have much longer dwelling times and would become uncomfortable. Local heating and/or additional clothing and regular rotation could provide the necessary level of comfort.

## 6.4 Adaptive Comfort

In recent years, a new approach has been introduced to assess thermal comfort: the adaptive temperature guideline. ASHRAE launched the project ASHRAE RP-884 to develop an adaptive model of thermal comfort and preference. The main findings can be found in de Dear and Brager (1998). The approach takes physiological feedback (acclimatization) and psychological feedback (habituation and expectation) into account. Opposed to Fanger's PMV model, which is based on laboratory steady-state experiments, it is based on field experiments. Adaptive thermal comfort is assessed using a graph showing acceptable limits for specific outdoor and indoor temperatures. In Fig. 6.4 an example of an adaptive guideline, specifically developed for the Netherlands (van der Linden et al., 2006) is presented. The clothing factor is included in the model but not explicitly: with changing outdoor temperature, people automatically change their clothing. Air velocity is unfortunately not included in the adaptive model. The visualization of the acceptable limits for different indoor/outdoor temperatures is very powerful for communication purposes.

## 6.5 Indoor Air Quality

The volume of fresh air that needs to be supplied (ventilation) can generally be kept very small for collection preservation. For human health, ventilation is important and regulated in law. In office buildings, Occupational Health Guidelines apply, requiring that approximately 35 $m^3$/h of fresh air per person needs to be supplied to maintain a healthy environment and to prevent sick building related syndromes. In public areas, the volume of fresh air which needs to be supplied can be adjusted according to the expected number of visitors, or based on the actual $CO_2$ levels. Obviously, ventilation rates should be related to the volume of the zone, since the visitors' impact will be greater for smaller volumes.

Besides ventilation, if air is also used for heating and cooling, a larger volumetric flow rate is required. In these cases, generally part of this larger air flow is recirculated. The total volumetric flow rate is therefore partly comprised by ventilation, and partly by recirculation. The ratio between the two components is usually adjustable and depends on the number of people present. Less ventilation usually

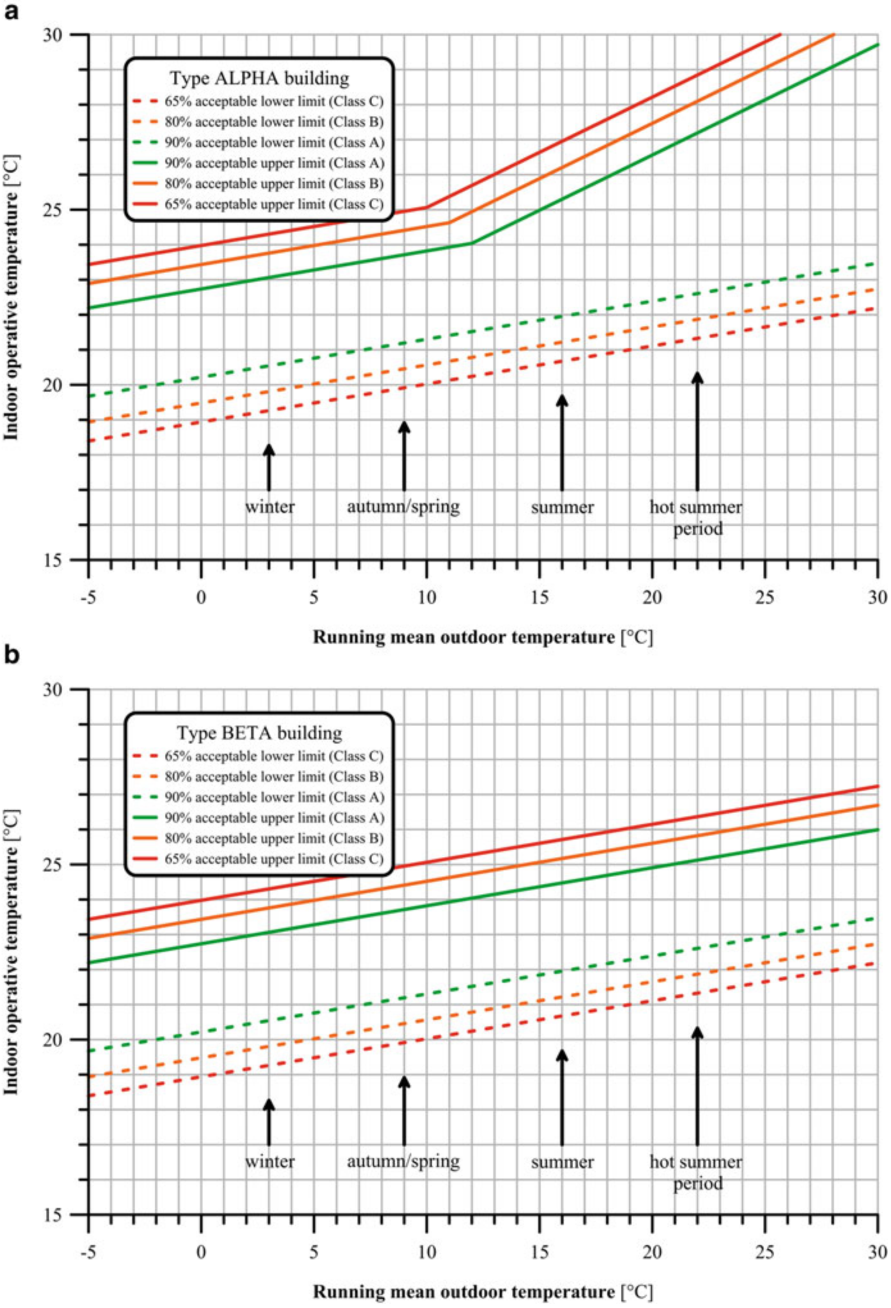

**Fig. 6.4** In the Adaptive Thermal model, thermal comfort is assessed via the operative temperature. The comfort limits depend on the outdoor climate. These figures are extracted from Van der Linden et al. (2006): figure (**a**) shows the comfort limits for an 'alpha' building in which the user has limited control over the indoor temperature by e.g. opening windows, while figure (**b**) shows the comfort limits for a 'beta' building in which the user has no influence over the indoor temperature (central HVAC system and sealed façade)

means less energy consumption. Especially since external air needs to be filtered, heated and have the humidity adjusted whereas the recirculated air will already be near the required values. When the outdoor conditions are favorable it might be beneficial in terms of energy savings to temporarily ventilate more. In exhibition rooms with high heat and cooling loads, and with a strict requirement for temperature uniformity in time and space, the total air volume is circulated (recirculation + ventilation) between six and eight times every hour. The amount of ventilation in well-attended exhibitions can increase up to 50 % of the total circulated air. This is high when compared to office situations where, depending on the type of control and system used, the total air volume circulates from one to three times per hour. In museum spaces with limited heat and cooling loads, less recirculation will suffice. In these cases, more attention could be paid to the spatial temperature uniformity. Temperature differences can be reduced by improved air mixing with individual fans or through adapted air supply using, e.g. swirl diffusers or high induction air jets. In such situations, the velocity of the air flowing over the objects surface should be taken into account and not be too high. Since research in this area is lacking, there are no numbers available. For the acclimatization of showcases in the Maritime Museum in Amsterdam the relation between air flow and object movement, i.e. movement of sails on a dummy ship model, resulted in a requirement of a maximum air velocity inside the showcase of 0.03 m/s (Lony 2008). The fact that this velocity was based on the visual movement of a miniature sail and not on an actual risk of mechanical damage indicates the complexity of the subject. For people the relationship between air speed and (dis)comfort has been studied and can be visualized (see Fig. 6.5).

Museums often employ all-air systems with high ventilation rates to prevent the formation of microclimates. Therefore, it is of utmost importance to evaluate the effect of the ventilation design on the air speeds in the occupation zone, especially since higher air temperatures in the countries with cold winter climates require higher air speeds. Another aspect that should be taken into account in cold winter climates, is cold air downdraught, which strongly reduces comfort levels. Cold air downdraught is the phenomenon that warm air at large cold surfaces, such as windows, cools down and then “falls” which makes it feel as if there is a constant cold draught. In most buildings where these phenomena can take place it is taken into account and mitigated: radiators are often placed under the window, so that the cold air is heated. Another strategy is to have proper window insulation so that cold air does not form a layer on the inside of the glazing.

Figure 6.6 shows a practical example of how surface temperatures in a historical building may differ as one part of the wall is exposed to the cold outdoor climate and the other part is adjacent to a warm indoor space. The cold inner wall may lead to thermal discomfort.

In tropical climates and during summer, higher air velocity helps to improve comfort, see Fig. 6.7. In some historic house museums during warm summer days mobile fans are positioned strategically, or even hand held fans are distributed, to improve local thermal comfort.

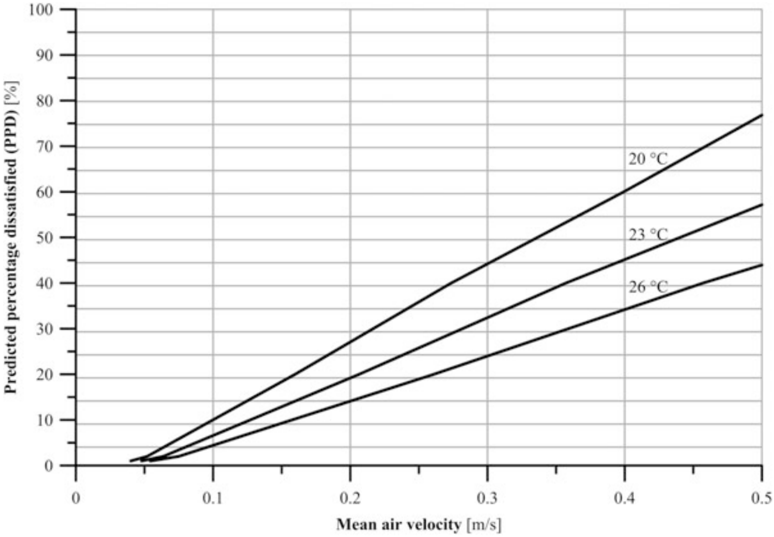

**Fig. 6.5** Percentage of People Dissatisfied (PPD) as Function of Mean Air Velocity (ASHRAE 2009)

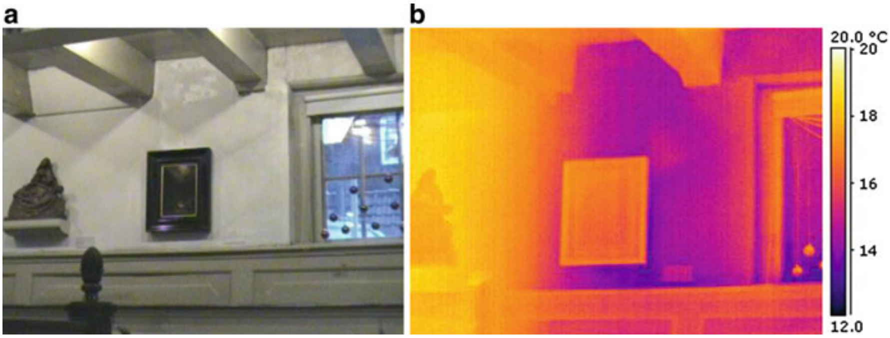

**Fig. 6.6** A standard (**a**) and an infrared image (**b**) of a wall that is partly adjacent to the outdoor environment. The infrared image shows that the surface temperature of the wall on the *left* is significantly higher than on the right side. This is due to the cold outdoor climate, resulting in radiation asymmetry and consequently discomfort. Also note the thermal shielding by the panel painting on the cold wall. The wall surface temperature behind the painting is lower, resulting in a very high relative humidity behind the painting (Photos: Neuhaus, Technical University of Eindhoven)

## 6.6 Alliesthesia

Another way of influencing potential discomfort could be by adapting the concept of alliesthesia (de Dear 2011). It describes the phenomenon that a stimulus can be given to generate a pleasant or unpleasant sensation, depending on the internal state

**Fig. 6.7** In hot climates options to increase thermal comfort are limited: increasing the air velocity is quite traditional. In this church in Olinda, Brazil, fans are placed on the walls to provide some comfort to the congregation during mass

of the subject. A museum example could be to have a room that is slightly too warm (a thermal overshoot) at the museum entrance, so that the possible colder sensation in the actual museum spaces becomes more pleasant. The inverse may apply for a summer period.

## 6.7 Uniform or Local Conditioning?

Conditioning the indoor climate, and providing thermal comfort, can be realized in the entire zone (uniformly), or in those regions where heating is locally required. Especially because the climatic needs for the collection generally differ from the thermal needs for occupants. Local conditioning may be much more effective and efficient in specific situations. A special case is the thermal comfort in churches in the Northern hemisphere. In many churches the air is heated by infra-red heaters or hot air. The hot air rises to the ceiling, heating up the higher parts of the church, resulting in large stratification and locally very low relative humidities. Since the congregation will occupy only the lower levels during mass most of the warm air is not efficiently used (Fig. 6.8). In the European '*Friendly Heating*' *project*: *Church heating and the preservation of cultural heritage*, the possibilities for local comfort were studied in detail (Camuffo 2010). It was found that electrically heated foil radiates sufficient heat and can be placed at strategic areas to heat the public. In this way, comfort is provided exactly where it is needed. In the CEN 15759 standard a compromise between heritage preservation and thermal comfort is proposed by accepting a thermal comfort that is 'slightly cool', with an average skin temperature of 30 °C (86 °F) to 33 °C (91 °F) (NEN-EN 15759-1 2011).

Consequently, energy costs decrease and negative effects on the collection are prevented. This is especially true for churches since they are generally heated intermittently. However, local conditioning may also be interesting for museums to reduce energy costs.

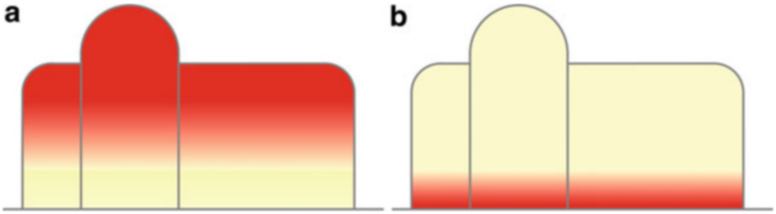

**Fig. 6.8** The two heating strategies: (**a**) central heating aims to provide even heat distribution throughout the building while also supplying heat to the building envelope. Most of the heat is accumulated in the *upper* part of the building (**b**) local heating aims to produce the best radiant temperature within the occupied area of the church only, with some local increase in air temperature and minimum draughts. The rest of the building remains almost unaffected and preserves or remains close to its historical climate

## 6.8 Conclusions

To conclude, it should be very clear that in geographic regions with cool to cold winters, heating is a major issue in climate control and consequently humidification to control the relative humidity. In tropical climate zones the temperature is high year round and cooling becomes a major issue and consequently dehumidification to control the relative humidity.

Obviously controlling the temperature for thermal comfort will influence the risks of chemical deterioration, biological decay and mechanical damage. Heating the indoor air will increase the risk of chemical decay of chemically unstable materials. In climate zones with (very) low outdoor temperatures, the relative humidity will drop and the risk of mechanical damage will increase. To reduce the risk related to low relative humidities, the indoor air could be humidified, which can increase the risk of biological decay, especially on cold surfaces. So, especially in cold climates it seems logical to accept a slightly cooler indoor climate to control these risks. Reducing thermal comfort will increase collection comfort and will reduce energy consumption. If the indoor climate is also humidified in winter to control RH, lower indoor temperatures will also reduce the required capacity for humidification and the risk of mold due to a lower condensation temperature.

In tropical climates however, maintaining a relatively low relative humidity and reduce indoor temperatures by cooling will reduce chemical and biological risks to the collection but may increase the risk of mechanical damage. Many objects in the collection will have been exposed for a very long time to much higher relative humidity levels. Reducing the relative humidity will also require substantial investments for climate control systems and the energy needed to run the machinery.

The result of this step is a list of climate zones within the building, or a floor plan in which the zones are indicated. For each zone the acceptable temperature and relative humidity ranges, based on human comfort requirements, are provided.

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# Chapter 7
# Step 6: Understanding the Indoor Climate

**Abstract** In this chapter the building's physical properties, which affect the indoor climate are described. The building is the first barrier between the outside and the inside. The different pathways from source, to effect, are presented. The impact of heat, air and moisture transport through, and thermal and hygric buffering, by the building envelope and within an enclosed space are described. Understanding the different properties that describe heat, air and moisture movement and their related transport mechanisms, helps understanding how the indoor climate is formed. Furthermore when the indoor climate is understood in more detail, a more balanced decision can be made as to why and how to change or improve the indoor climate in a passive way by small (or large) alterations to the building.

**Keywords** Building physics • First barrier principle • Heat • Moisture • Air • Indoor climate

## 7.1 Introduction

In Chaps. 4, 5, and 6 the climate needs for the collection, buildings and users are described. Based on the application of this information to a specific case study, the climate specifications can be defined. But before these specifications are quantified and a first concept of a mitigation strategy is developed insight into how the indoor climate forms is essential. The unique combination of any form of active climate control and the way the building produces a specific indoor climate should be understood in detail.

The transport of heat, air and moisture as defined by the outdoor climate, building envelope and climate systems will be different for all the zones in a building. These specific building physical properties will define the climate near collections, the historic interior and the people visiting or working in the building. If the indoor climate generates unacceptable risks to the collection, the building and its finishes, modifying the building and/or the climate system can mitigate those risks, as can moving the collection or changing the use of certain rooms.

Most buildings that house collections were not designed with today's functionalities and demands in mind. This means that these old buildings will have been adapted step by step to meet the museum's requirements in terms of safety and security, light, pollution and indoor climate control. Generally buildings are

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Cultural Heritage Science, DOI 10.1007/978-3-319-34241-2_7

restored and refurbished approximately twice every century. So, many historic buildings, including the ones with historic interiors, have changed quite drastically from their original appearance. In the past decades these adaptions to meet the new requirements are much more drastic and intrusive than of those in earlier years. Central heating and the transport of climatised air through the building required large systems to be introduced into the building. Modifying a building's fabric and/or the hygrothermal balance can result in the introduction of new risks. Understanding the building's physical properties, and the way these affect the indoor climate, is essential to be able to develop scenarios to understand and mitigate climate risks within the limitations and possibilities of the building.

## 7.2 First Barrier Principle

To gain insight into how the climate in a building/zone and close to the object is formed, it is obvious to look from the outside in. Questions can be asked to become better informed, such as: how and to what extent will outside air penetrate into the building? Will the hygrothermal conditions of the air change after entry? Is the temperature inside different than outside? Is moisture released or absorbed (moisture buffering) by the building, the interior, the collection and/or people? Is the air actively humidified, dehumidified, heated or cooled? To understand the way the indoor climate is formed one needs to understand the behavior of the building, the furnishing, equipment and use of the building. A relatively simple method to understand how the indoor climate in a building, zone, room, or near the object, is formed, is to properly study the pathway from outdoor heat and moisture sources, to the exposed objects and/or finishes and to distinguish all the barriers between source and object. The way in which the indoor climate is finally created is a complex interplay of various internal and external factors.

Starting outdoors, the most important heat source is the sun and the air temperature, important moisture sources are the absolute humidity of the air, determined for example by rain. Outdoor air will enter the building by controlled (ventilation) or by uncontrolled processes (infiltration). The air enters the building with a temperature and specific humidity that might be changed; changing the temperature by cooling or heating and/or by adding or removing moisture. Heat sources will add energy, while heat sinks will subtract energy from the air resulting in a higher or lower temperature. Moisture sources will add moisture, while moisture sinks will subtract the moisture content of the air. The capacity of these sources and sinks determines whether the temperature or the specific humidity inside is higher or lower than outside.

Two major outdoor sources can be distinguished: the sun as the source of thermal energy, heat, and rain as the source of water and water vapor, moisture, see Fig. 7.1. From these sources several lines are drawn: red lines for heat flow and green for moisture flow. These are the pathways that indicate how heat and moisture are being transferred from the outdoor to the indoor and vice versa. In the yellow boxes the absolute humidity and temperature are combined to give the relative humidity. Note that although the relative humidity plays a very important role in the indoor climate risks it is the temperature and absolute humidity that can be controlled.

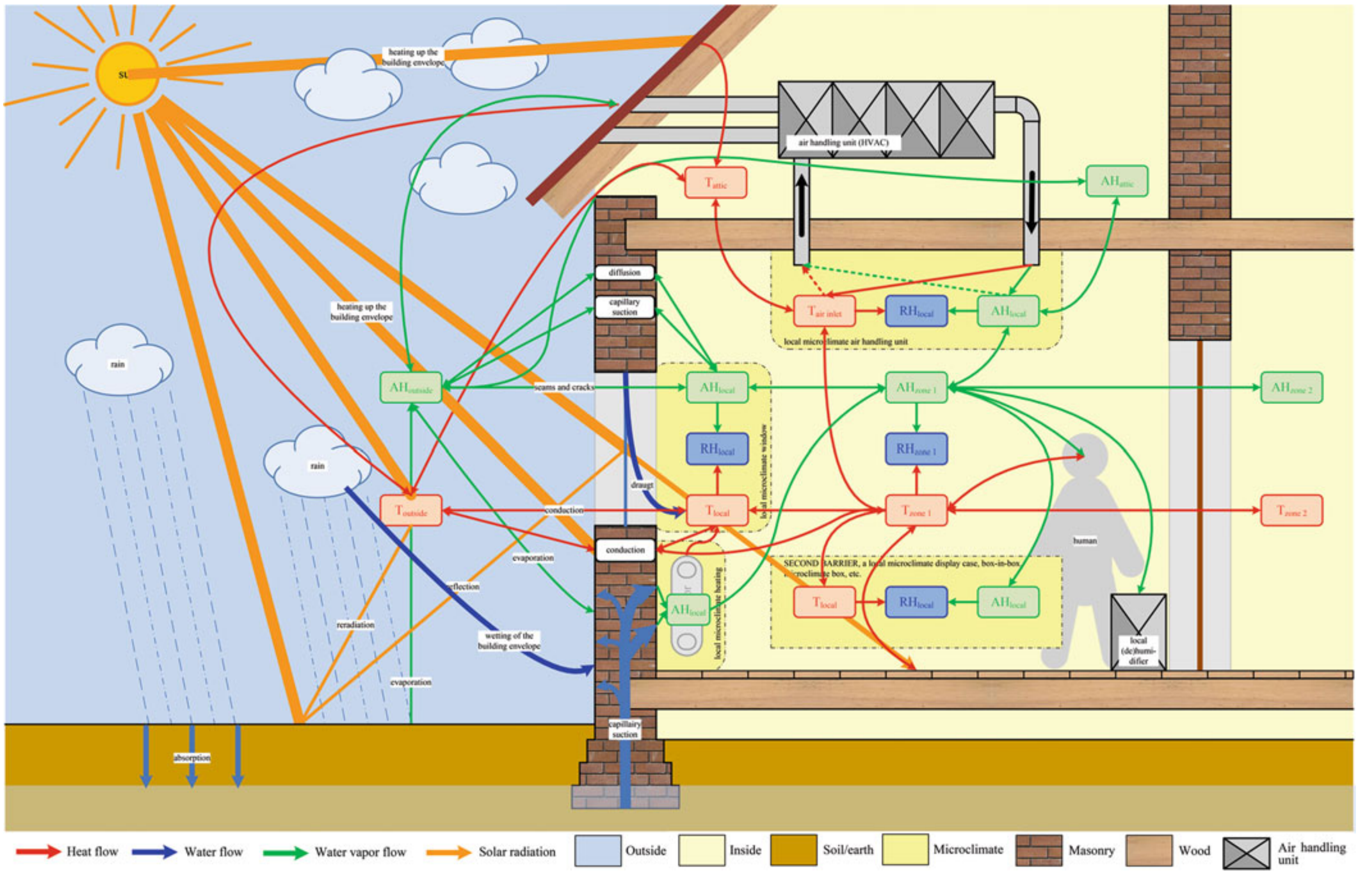


**Fig. 7.1** Pathways from outdoor sources (sun and rain) to the received indoor climate

The most important outdoor heat source is the sun. The sun contributes in two different ways to the heating of a room. First (indirectly) when solar radiation heats up the earth, i.e. soil, buildings, pavement, etc. When a surface is hit by solar radiation this surface will heat up and start reradiate heat into the environment and produce a certain outdoor temperature ($T_{outdoor}$). When a façade or roof absorbs solar radiation, the material will become warmer and heat is transported through the building envelope to the inside. It is important to recognize that some of the absorbed thermal energy can also be stored within the mass of the building envelope. When solar radiation enters the building through the glazing system the indoor temperature ($T_{zone}$) will increase in a similar way by re-radiation of absorbed thermal energy. Internal heat sources like radiators or cold sources like cooling units will of course also influence the indoor room temperature. Finally the temperature in the zone is interrelated with the temperature of the adjacent zones, partly by conduction but mainly by convection processes.

The most important outdoor moisture source that influences the outdoor absolute humidity ($AH_{outdoor}$) is rain. Rainwater will be absorbed by the earth and the building facade. Evaporation from the earth or façade will lead to an increase of the absolute humidity of the outdoor air and thus the partial vapor pressure. Rainwater absorbed by the ground can also be transported into the building by capillary suction through the foundation of the building, as illustrated by the blue arrows in Figs. 7.1 and 7.32. Rainwater absorbed by the façade can be transported through the wall as water and water vapor by capillary suction and diffusion, respectively. Moisture can also be stored by the building envelope. Moisture sources, like people and plants, and moisture sinks, like thermal bridges, also influence the indoor absolute humidity. Finally the absolute humidity of the zone will also depend on the absolute humidity of the adjacent zones by convection mainly. Especially when damp cellars are involved. The absolute humidity may also differ inside from the outside due to a time delay effect caused by the flow rate of incoming air (i.e. air exchange rate) and moisture ad- or desorption (i.e. buffering) by the building mass, the interior finishes and/or the collection.

The relative humidity is a result of the temperature and absolute humidity. Pressure differences, resulting from temperature differences, will efficiently mix the absolute humidity. The absolute humidity can therefore be assumed to be more or less uniform within a zone. Gradients will be formed near air inlets of an HVAC-system and stand-alone (de)humidifiers. The local relative humidity is thus a result of the local temperature and the absolute humidity in the zone.

Finally, the relative humidity in the vicinity of the object can be determined by a second barrier, such as a bag, box or showcase that might enclose the object. The leakage rate, buffering capacity and thermal resistance determine the way the specific humidity and temperature of the zone influences the climate around the object, as described for the climate in the zone. The local relative humidity is further determined by the presence of buffering materials (hygroscopic packing materials and/or other objects).

For both temperature and moisture, seams and cracks will allow air to ex- or infiltrate (uncontrolled air flow) through the building envelope. The opening of windows and doors will allow for ventilation (controlled air flow), just like HVAC-systems. In this way heat energy and moisture is transported relatively quickly, since conduction and diffusion are slow processes and related to the thermal and hygric mass of the building. The characteristics of the building envelope determines to what extent the outdoor climate determines the indoor climate. Important properties of the building envelope that need to be considered are:

- Resistance to heat and cold;
- Resistance to water and water vapor;
- Buffering of heat (and cold) and water (and water vapor);
- Air permeability of the building envelope (in- and exfiltration).

These properties all together act as a first barrier that separates the outdoor climate from the indoor climate, and can be adjusted to help maintain a suitable indoor climate. Obviously, full climate control by HVAC and/or a (central) heating system greatly affects the indoor climate but the final climate class that can be maintained depends on the building physics.

## 7.3 Heat

The most important outdoor heat sources or sinks are air temperature and solar radiation. When the outside temperature differs from the inside temperature, a gradient over the building envelope is formed. If the outdoor temperature is lower than the indoor temperature the indoor air will lose heat to the outside (Fig. 7.2a) and vice versa (Fig. 7.2b).

The amount of heat gain or loss through the building envelope depends on the thermal resistance of the building materials used in the construction. Thick walls have a higher thermal resistance than thin walls made of the same material. However, improving the thermal resistance of buildings in cold climates is not efficient by only adding more of the same material, i.e. increasing thickness. Much more effective is

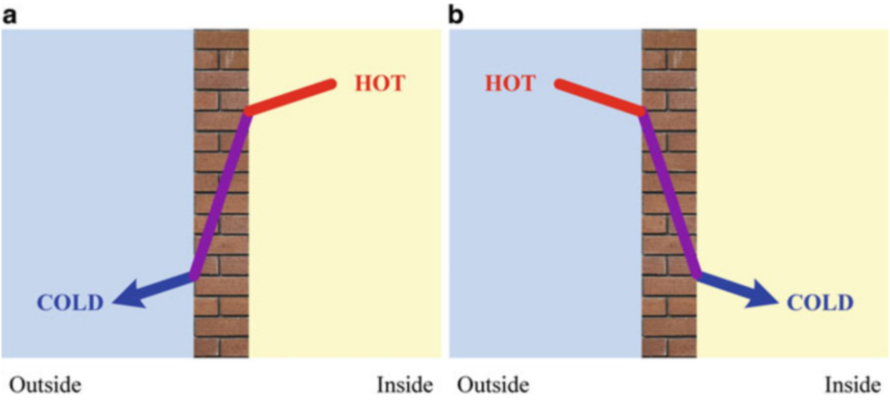


**Fig. 7.2** A schematic representation of heat transfer through a wall (**a**) from the warm inside to the cool outside (typical winter situation in cold climates) and (**b**) from the warm outside to the relatively cool inside (typical situation in a tropical climate)

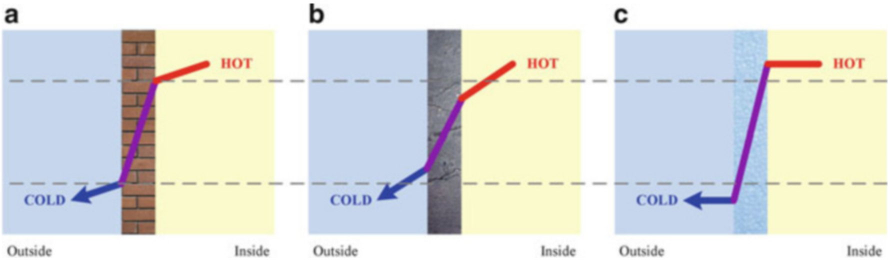


**Fig. 7.3** A schematic representation of temperature gradients in different types of materials with similar thickness (**a**) brick, (**b**) concrete, both with a low thermal resistance and thus a small drop in temperature, and a large difference between the indoor and surface temperature (**c**) polystyrene, with a high thermal resistance and thus a large drop in temperature, and a small difference between the indoor and surface temperature

adding a material with a lower thermal conductivity which will decrease the thermal conductivity of the whole wall. The rationale is that when a non-insulating material (i.e. brick) is compared with an insulating material (i.e. mineral wool) with similar thickness, mineral wool will transfer less energy than brick per square meter for a given temperature difference. The result is that indoor surface temperatures of an uninsulated wall will be lower than the indoor air temperature, while the indoor surface temperature of an insulated wall will be close to the indoor temperature. This effect is illustrated in Fig. 7.3 for brick, concrete and polystyrene of similar thickness.

Brick is a relatively good thermal conductor. The outside surface temperature (Fig. 7.3a) will be slightly higher than the outside air temperature. The inside surface temperature will be slightly lower than the indoor air temperature. This will result in a relatively large temperature gradient over the brick wall. Concrete is a more effective thermal conductor (less effective insulator) than brick. Therefore the temperature gradient over the concrete wall will be much smaller (Fig. 7.3b). As a result the indoor surface temperature will be even lower and the outdoor surface temperature will be higher when compared to the surface temperatures of a brick wall. Insulation materials, like mineral wool, polystyrene or polyisocyanurate have very low thermal conductive properties (Fig. 7.3c). The temperature gradient within the material will therefore be very large. The inside surface temperature will be almost equal to the indoor air temperature and the outside surface temperature will be almost equal to the outdoor air temperature. Obviously, when the outdoor temperature is much higher than the inside temperature, the opposite gradients are formed in these materials.

At low outdoor temperatures, the building envelope can be significantly heated by solar gain. This means that indoor surface temperatures can be significantly higher than expected based on only outdoor air temperatures. Figure 7.4 shows the temperature gradients for an uninsulated (Fig. 7.4a) and an insulated (Fig. 7.4b) wall. The solid lines show the temperature gradients with solar gain and the dashed line without solar gain with low outdoor temperatures (winter) and high outdoor temperatures (summer). Both outdoor and indoor temperature are kept constant in this example to clearly see the influence of the solar gain. As can be seen, the indoor surface temperature increases significantly due to solar gain. In reality high solar gain will of course increase the indoor temperature, but the extent will depend on heat losses by transmission and ventilation.

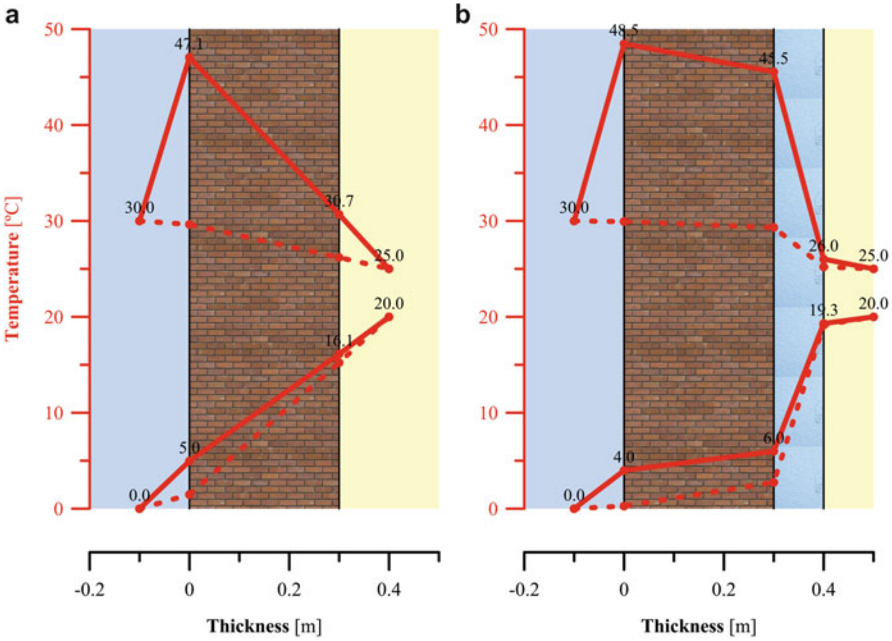


**Fig. 7.4** Calculated surface temperatures with (*solid line*) and without (*dashed line*) solar radiation for a non-insulated (**a**) and insulated (**b**) brick wall

The total rate of heat gain or loss for a building depends on:

- The temperature difference between in- and outside;
- The material's thermal conductivity properties (i.e. thermal insulation);
- The thickness of the various layers of the building envelope;
- Leakiness of the building (the so-called air exchange rate: AER)

Depending on the outdoor climate, i.e. geographical location and the time of the year, the indoor air will gain or lose heat. In temperate climates especially, humans protect themselves from low and high temperatures by blocking the outdoor climate using materials with good insulation properties (low conductivity, see Table 7.1 in the next paragraph). In hot or very cold climates it is much more difficult to maintain a suitable and comfortable indoor temperature using only passive means, i.e. building physics. The use of additional systems for heating or cooling are generally required to meet human comfort requirements. For people, comfortable temperatures range from a lower limit of 17 or 18 °C (63–64 °F) to an upper limit of 25 °C (77 °F) (see Chap. 6) depending on the outdoor temperature. Objects and building fabrics also have optimal temperatures at which they are best preserved (see Chaps. 4 and 5).

### 7.3.1 Understanding Heat Transfer

Heat or energy can be transported by three different processes: conduction, radiation and convection as shown in Fig. 7.5.

**Table 7.1** Conductivity coefficient of different building materials

| Material | | Conductivity [W/mK] | |
|---|---|---|---|
| Insulation | Traditional (e.g. mineral wool) | 0.04 | Low |
| | Capillary active (e.g. calcium silicate) | 0.06–0.065 | ↓ |
| Wood | | 0.14–0.17 | |
| Gypsum board | | 0.23–0.46 | |
| Plaster | | 0.52–0.93 | |
| Brick | | 0.60–0.70 | |
| Concrete | | 2.00 | High |
| Metals | | 52–372 | Very high |

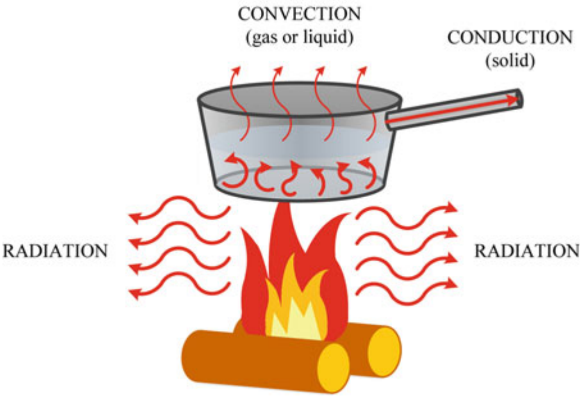


**Fig. 7.5** Visualization of conduction, radiation and convection

Conduction is the energy transfer within a material due to a temperature difference (symbol: $\Delta T$ or $\Delta\theta$, unit: °C or K). Considering the indoor climate, the most likely conduction takes place between the inner and outer surface of an external wall. A large temperature difference will result in a large heat transfer and vice versa. Obviously, some materials, like metals, conduct heat much easier than other materials, such as wood. Materials with a high thermal conductivity are widely used in cooling applications for combustion engines or electronic devices and materials with a low thermal conductivity are used as thermal insulation. The larger the thermal conductivity of a material (symbol: $\lambda$, unit: W/mK), the larger the heat transfer and the larger cooling or heating ability. In Table 7.1 the conductivity of some common materials is presented.

Thermal radiation is an electromagnetic wave generated by the thermal motion of charged particles in a material. Every material with a temperature above absolute zero (0 K, −273 °C, −459 °F) emits radiation. This means that a cold and a warm mass facing each other, will constantly exchange radiant heat. The warm body will cool down and the cold body will heat up. A person with an average body temperature of 37 °C (99 °F) in the vicinity of a cold surface, such as a window with a much lower temperature, e.g.7 °C (45 °F), will exchange heat and will experience the cold surface. The amount of heat transfer depends on the surface temperature and the emissivity coefficient (symbol: ε, unit: dimensionless ratio) of the material. It is important to understand that energy is mainly exchanged in the infrared part of the electromagnetic spectrum and that the emissivity coefficient depends on the wavelength. An example to explain this phenomenon is the low emissivity coefficient of about 0.2 of the color white in the visible part of the spectrum (low emission, low absorption, high reflection). But in the infrared part of the spectrum the emissivity coefficient is about 0.9 (high emission, high absorption, low reflection). So the color white acts as 'black' in the infrared part. This indicates that the human eye is not able to properly estimate the emission coefficients of surfaces.

The amount of energy that can be exchanged between a surface and it's surroundings is directly related to the emissivity coefficient of that specific material. Materials, such as wood, stone and marble with a high emissivity ($\varepsilon = 0.9$–1) emit energy much more readily than materials with a low emissivity ($\varepsilon < 0.2$) such as polished silver and gold. In general one number is given for the emissivity coefficient over a series of wavelengths at a specific temperature (Table 7.2).

Thermal cameras visualize an infrared image based on the amount of energy that is radiated by surfaces. Generating a false color image, with colors indicating different surface temperatures. Since this temperature calculation is based on the Stefan–Boltzmann law using the emissivity coefficient, it is important to use the correct coefficient.

Convection is the collective movement of molecules within liquids and gases, including diffusion processes. Within buildings convective air movement is air moving near surfaces allowing energy transfer between surfaces and air. The amount of energy that is transferred depends on the temperature difference (symbol: $\Delta T$ or $\Delta\theta$, unit: °C or K) and the air velocity near the surface (symbol: $v_a$, unit: m/s). If there is no temperature difference or the air velocity is zero, then no energy will be exchanged. Cooling or heating of a surface will occur when the temperature differences and the air velocity are higher. This is the reason why strong winds are generally experienced as being colder than the actual air temperature (so-called wind chill). Heating systems strongly depend on the principles of convective air movement. Warm air generated by hot radiators rises and when cooler air is being supplied e.g.by an HVAC system, effective air circulation is created.

### 7.3.2 Heat Sources

As illustrated in Fig. 7.1 the indoor climate is influenced by external and internal heat sources. Generally the sun is the most significant and influential external heat source. Its energy will be transported by glazing systems. Unlike walls and roofs, the transmission of energy by glazing systems is rather unhindered because of its transparency. Transmitted solar energy will heat up internal surfaces. In turn these surfaces will heat up and start to reradiate this energy back into the room, making those surfaces internal heat sources.

**Table 7.2** Emissivity coefficient of different building materials (FLIR Systems Inc. 2011)

| Material | Emissivity coefficient [−] | Wavelength [μm] | Temperature [°C (°F)] |
|---|---|---|---|
| Aluminium (foil) | 0.09 | 3 | 27 (81) |
| Aluminium (foil) | 0.04 | 10 | 27 (81) |
| Aluminium (roughened) | 0.18 | 10 | 27 (81) |
| Aluminium (weathered, heavily) | 0.83–0.94 | SW | 17 (63) |
| Basalt | 0.72 | | |
| Brass (oxidized) | 0.03–0.07 | LW | 70 (158) |
| Brass (oxidized) | 0.04–0.09 | SW | 70 (158) |
| Brass (sheet, rolled) | 0.06 | T | 20 (68) |
| Brick (firebrick) | 0.75–0.93 | SW | 17 (63) |
| | 0.68 | | |
| Brick (masonry) | 0.94 | SW | 35 (95) |
| Brick (masonry, plastered) | 0.94 | T | 20 (68) |
| Concrete | 0.93–0.94 | T | 20 (68) |
| Concrete (rough) | 0.97 | SW | 17 (63) |
| Copper (commercial, burnished) | 0.07 | T | 20 (68) |
| Copper (oxidized, heavily) | 0.78 | T | 20 (68) |
| Copper (polished, mechanical) | 0.015 | T | 22 (72) |
| Glass | 0.92–0.94 | | |
| Gold (polished) | 0.018 | T | 130 (266) |
| Granite (polished) | 0.85 | LLW | 20 (68) |
| Granite (rough) | 0,88 | LLW | 21 (70) |
| Gypsum board | 0.80–0.95 | T | |
| Human skin | 0.98 | T | 32 (90) |
| Insulation (general) | 0.90[a] | | |
| Iron and steel (oxidized) | 0.74 | T | 100 (212) |
| Iron and steel (polished) | 0.07 | T | 100 (212) |
| Iron, cast (oxidized) | 0.63 | T | 38 (100) |
| Iron, cast (polished) | 0.21 | T | 38 (100) |
| Lead (oxidized, gray) | 0.28 | T | 20–22 (68–72) |
| Paint (oil) | 0.87 | SW | 17 (63) |
| Paper (black) | 0.90 | T | |
| Paper (white) | 0.70–0.90 | T | 20 (68) |
| Plaster (plaster board) | 0.91 | SW | 20 (68) |
| Silver (polished) | 0.03 | T | 100 (212) |
| Tin (burnished) | 0.04–0.06 | T | 20–60 (68–140) |
| Varnish (flat) | 0.93 | SW | 20 (68) |
| Wood | 0.88–0.93 | T | |
| Wood (pine) | 0.67–0,75 | SW | 70 (158) |
| Wood (planned Oak) | 0.99 | T | 20 (68) |

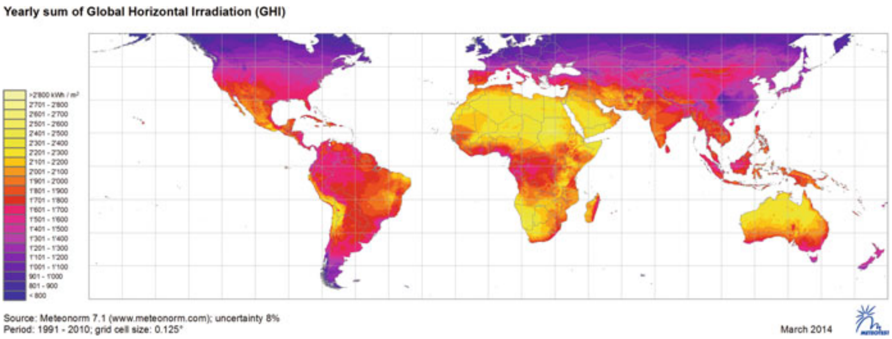
(continued)

**Table 7.2** (continued)

| Material | Emissivity coefficient [−] | Wavelength [μm] | Temperature [°C (°F)] |
|---|---|---|---|
| Wood (pine) | 0.81–0,89 | LW | 70 (158) |
| | 0.95 | | |
| Zinc (polished) | 0.04–0.05 | T | 200–300<br>(392–572) |

*T* total spectrum 2–20 μm, *SW* shortwave 2–5 μm, *LW* long wave 8–14 μm, *LLW* long long wave 6.5–20 μm

[a]This number is taken from De Wit (2009), p 10



Source: Meteonorm 7.1 (www.meteonorm.com); uncertainty 8%
Period: 1991 - 2010; grid cell size: 0.125°

March 2014

**Fig. 7.6** Yearly sum of the global horizontal irradiation (Source: © METEOTEST; taken from www.meteonorm.com)

Internal sources, especially in cold countries include radiators, which can be as hot as 70–90 °C (158–194 °F), and generate heat ranging from 1,700 to 2,700 W/m$^2$. Human beings are also heat sources, generating 80–300 W per person depending on their activity. Especially when larger groups are present for prolonged periods of time this source can become relevant. Electrical equipment such as lighting and computers will also generate heat. Lighting will typically generate heat ranging from 2.5 to 20 W/m$^2$. Office equipment like computers, printers etc. will generate about 100 W per computer or printer (or 10 W/m$^2$). More detailed information can be found in ISSO 33 (1996).

The sun emits a lot of energy, but only 1,350 W/m$^2$ (Hermans 2008) will reach our planet's surface, and can be absorbed and transformed into heat. This effect is called solar gain and the amount depends on the orientation and geographical location. In Fig. 7.6 the yearly sum of Global Horizontal Irradiance (symbol: GHI, unit: W/m$^2$) is shown for the world. The Global Horizontal Irradiance is the total amount of shortwave radiation (visible, near-ultraviolet and near-infrared radiation) received from above by a horizontal surface.

As the earth rotates, solar gain varies from day to day. Due to geographical location, the seasonal and hourly position of the sun changes. For two geographical locations Indonesia and The Netherlands the shading in January and July of a building is given for three different times: 8:00, 12:00 and 16:00 (Fig. 7.7).

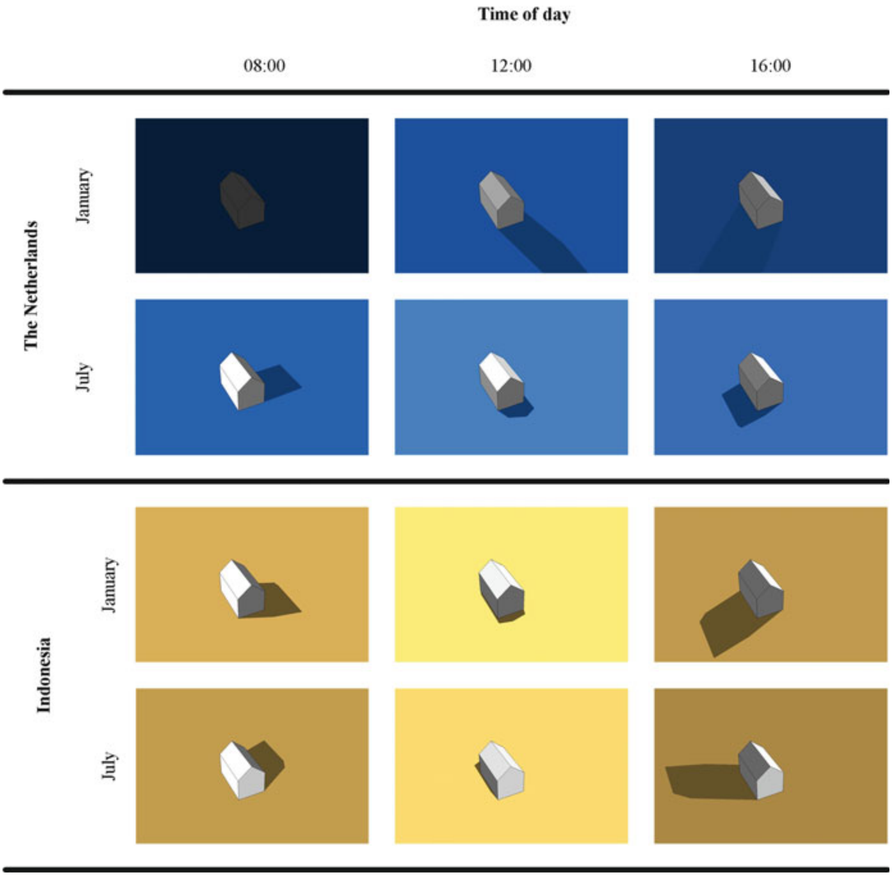


**Fig. 7.7** Shading of a simple building at two locations (Indonesia and the Netherlands) for two seasons (January and July) at three times (8:00, 12:00 and 16:00)

From Fig. 7.7 it can be seen that in Indonesia the shadows in the morning have a slightly different direction. In the afternoon the shade is almost gone, i.e. the sun in both January and July is directly above the building. This means that high solar gains affect the roof most and the east and west walls next. For the Netherlands it can be seen that in January daylight is available for a short period of time. The sun rises at 8:00 and sets at 16:00. The shadow at 12:00 is very long. This means that the angle between the earth and the sun is small and therefore the total solar gain will be small. But the amount is still enough to be used to passively heat buildings (Department of Industries 2014; Cairns Regional Council 2011). In July daylight is available for a longer period. Both the roof and south, east and west walls are heated. These sun path patterns are generally well known to local people and this knowledge can be used to better estimate the effect of solar radiation.

When the sun heats up a window, the amount of heat transferred by the window depends not only on the conductive properties of the glass but also on the

**Table 7.3** Overall heat transfer coefficients of different glazing systems and window frames (Taken from: NPR 2068:2002)

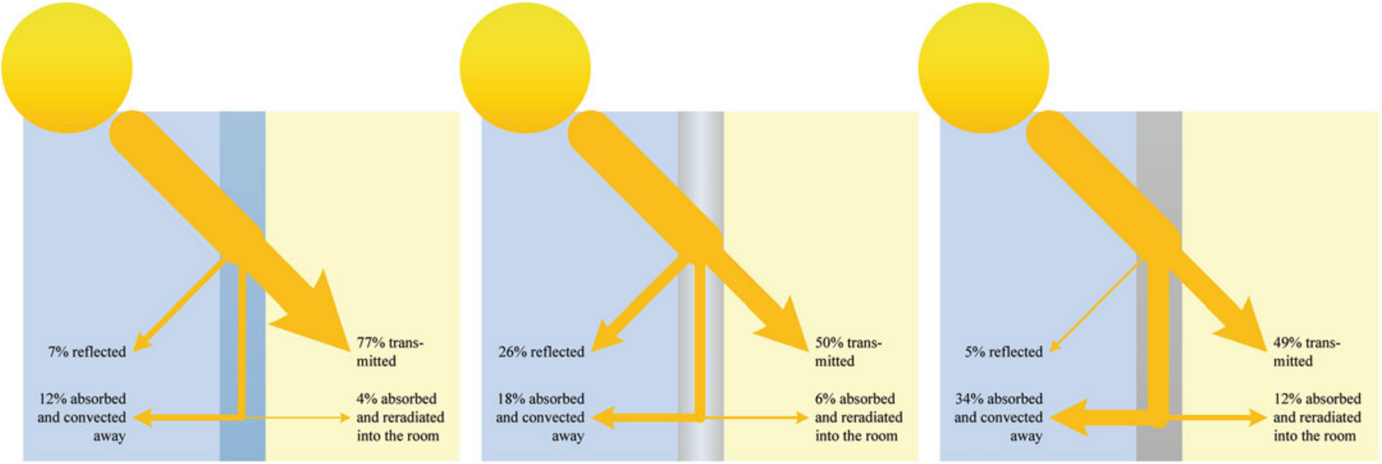
| Glazing system | Overall heat transfer coefficient (U-value) [$W/m^2/K$] | | | |
|---|---|---|---|---|
| | | Window frame | | |
| | Glass | Wood or plastic | Metal, with thermal break | Metal, without thermal break |
| Single | 5.8 | 5.2 | 5.4 | 6.2 |
| Double | 2.8 | 2.9 | 3.3 | 4.1 |
| HR++ | 1.2 | 1.8 | 2.2 | 3.0 |
| | 1.0 | 1.6 | 2.1 | 2.9 |

conductive properties of the window frame. In Table 7.3 the overall heat transfer coefficient, the so-called U-value, is given for different glazing systems and window frames. The higher this U-value the worse the thermal performance of the material or building component. A low U-value usually indicates high levels of insulation. From this table it can be seen that the window frame plays a significant role in the overall performance when used in combination with energy efficient glazing, also called HR++ glazing or low e-glass.

The key purpose of windows is to allow sunlight to enter the building and to create a welcoming and comfortable atmosphere. When sunlight hits a window some radiation is reflected (symbol: $\rho$, unit: dimensionless ratio), some absorbed (symbol: $\alpha$, unit: dimensionless ratio), but most will be transmitted (symbol: $\tau$, unit: dimensionless ratio). For normal glass panes with a width of 4 mm, approximately 81 % of the solar radiation is transmitted to the inside. This is called the Solar Heat Gain Coefficient (SHGC or G-value), which can be defined as the quotient of the transmitted radiation, plus a portion of the absorbed solar radiation and total solar radiation. Reducing solar gain of interior spaces, is most efficiently done by increasing the reflection and reducing the transmittance and absorption characteristics of the transparent parts (Fig. 7.8). This can also be achieved by applying special filters to the (historic) glass (see Chap. 9).

In order to lower energy consumption for buildings in the northern Hemisphere during winter, the solar energy entering through windows can be used. In winter, solar gain will help to heat up the building decreasing energy demand for heating. In summer however solar gain needs to be limited to prevent overheating and thus increasing the energy demand for cooling. When choosing a new glazing system or adjusting the existing glazing system it is essential to have some kind of adjustable system to vary the SHGC depending of the season. In Table 7.4 the SHGC are provided for various glazing systems and internal and external shading systems.

In museum Oud-Amelisweerd, Bunnik, The Netherlands (Figs. 7.9 and 2.2) a high-tech dynamic solution was implemented. Entrance of daylight was required to enjoy the historic wall finishes and the other works of art, but an excess of solar gain needed to be avoided to minimize fluctuations in temperature and relative humidity. Especially since the modest HVAC-system (see also Sect. 2.6, Fig. 2.3) that was implemented has a limited capacity. The louvres on the south façade were reconstructed and mechanized (Fig. 7.9b). A high-tech system controls the



**Clear glass**

| | |
|---|---|
| reflectance | 7% |
| absorptance | 16% |
| direct transmittance | 77% |
| SHGC or G-value | 0.81 |

**Reflecting glass**

| | |
|---|---|
| reflectance | 26% |
| absorptance | 24% |
| direct transmittance | 50% |
| SHGC or G-value | 0.56 |

**Heat absorbing glass**

| | |
|---|---|
| reflectance | 5% |
| absorptance | 46 |
| direct transmittance | 49% |
| SHGC or G-value | 0.61 |

**Fig. 7.8** A schematic representation of reflection, absorption and transmission properties of single clear, reflecting and heat absorbing glass panes

**Table 7.4** Solar heat gain coefficients of various glazing systems and internal and external shading systems

| System | SHGC [−] |
|---|---|
| Clear glass (Fig. 7.8) | 0.81 |
| Reflecting glass (Fig. 7.8) | 0.56 |
| Heat absorbing glass (Fig. 7.8) | 0.61 |
| Clear double glazing (ISSO 33) | 0.70 |
| Clear single or double glazing with internal sun screen (ISSO 33) | 0.45 |
| Clear single or double glazing with external sun screen (ISSO 33) | 0.15 |
| Clear single glass with filter | 0.39–0.64[a] |
| Clear double glass with filter | 0.29–0.56[a] |

[a] Depending on type of filter. Data taken from datasheets from various types of filters from various types of manufactures

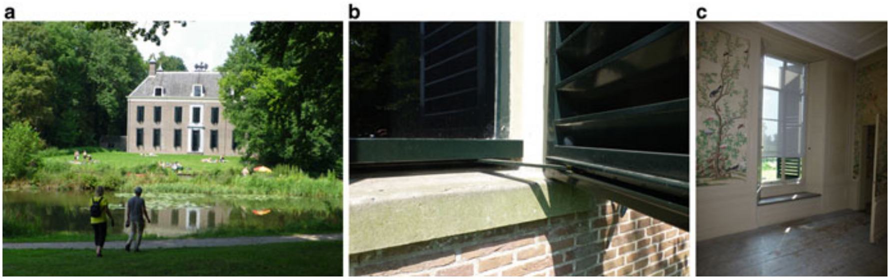


**Fig. 7.9** Sunlight control of Museum Oud-Amelisweerd in Bunnik, The Netherlands: (**a**) the exterior of the museum, (**b**) the reconstructed and mechanized louvers as external shading system and (**c**) the electrified sun screens as internal shading systems

opening-closing based on in- and outdoor solar radiation measurements. The louvres are combined with internal mechanized sun screens (Fig. 7.9c). Both systems work together in order to keep solar gain to a minimum, whilst keeping visibility to a maximum. Filters placed on the existing glazing blocks all UV-radiation.

As shown in Fig. 7.8 the absorption of solar radiation by the clear glass window, is about 16 %. For non-transparent building parts, such as walls, the absorption of solar radiation is much higher (75–95 %, Table 7.2). Figure 7.4 shows that the effect of solar gain on the surface temperature can be quite large for an outdoor surface like a façade or roof. This can lead to internal stresses in the building fabric. In Pilette and Tayler (1988) the effect of partial shading on three types of window panes was investigated. The study showed that thermal stresses in the glass panes doubled when compared to fully shaded windows.

Figure 7.10 shows the heating of a historic interior by direct sunlight. As can be seen, sunlight penetrates deep into the room and hits the side of the fireplace. The thermogram on the right shows surface temperatures of 36 °C (97 °F), while the surrounding interior finishes are 20 °C (68 °F).

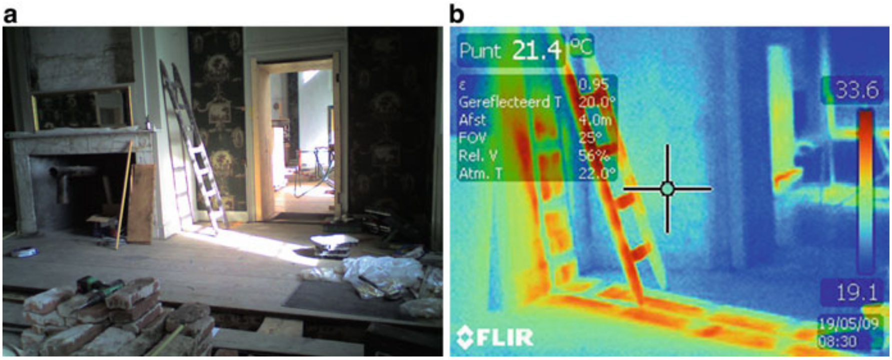


**Fig. 7.10** Sunlight entering a historic interior increasing surface temperatures. A picture of a room with paper hangings during restoration (**a**). The surface temperatures are clearly influenced by the incoming solar energy, as can be seen on the thermal image (**b**)

The increased temperatures will cause a local drop in relative humidity. Obviously, these kind of relative humidity gradients can lead to mechanical damage as described in Chap. 4. Surfaces with temperatures increased above the ambient indoor temperature will radiate heat back into the room, acting as small radiators and further increasing the indoor temperature. Obviously, when culturally important surfaces such as paintings, are hit by direct sunlight local temperature and relative humidity gradients can reach levels that cause significant risks to the object.

This heating process is similar to the greenhouse effect, where absorbed heat is prevented from leaving. A greenhouse is built of materials that allow transmittance of sunlight, usually glass, sometimes plastic. Interior surfaces absorb the short infrared wavelengths radiation and reradiate the heat at longer infrared wavelengths. Glass can only transmit short wavelength radiation and not the long reradiated wavelengths. As a result the indoor temperature increases further leading to significant heating of the interior. The greenhouse effect has become a well-known phenomenon in the context of global warming.

Traditionally buildings in cold climates were actively and locally heated by means of a fireplace or coal stove. In the 1950s these were replaced by central heating systems with a central heating source coupled to heating panels in every room. The purpose of those heating panels is to compensate for energy losses from the building and to create a more uniform comfortable environment. Since these panels are kept as small as possible, relatively high surface temperatures need to be generated to transfer enough heat. Generating convective airflows and radiating heat in all directions, results in locally higher temperatures and lower relative humidities. As illustrated in Fig. 7.11 radiators close to cultural objects can locally influence the climate around these objects and parts of building. Please note that in this example the temperature was maintained at a relatively low level to reduce the risk of drying of the oil painting on canvas.

**Fig. 7.11** A painting hanging over a radiator, with a low temperature set point (**a**). In the thermal image (**b**) a subtle heating of the underside of the canvas painting can be clearly seen

### *7.3.3 Thermal Bridges*

A thermal bridge is a shortcut in the building envelope. A part of the building which allows for high heat transfer when compared to the surrounding building materials e.g. a metal cramp in a masonry wall. Thermal bridges result in locally high heat transfer and thus locally low temperatures and need to be avoided. This phenomena is very common in the northern hemisphere when insulation is added to the outer wall. Insulation can be added on the outside or on the inside of the building. Sometimes the wall cavity can be filled with insulation material. For insulation added to the outside of the outer wall and filled in wall cavities, these shortcuts are typically the existing windows and door reveals. For insulation added to the inside of the outer wall there are other potential penetration points that might be formed, such as joints between external and internal walls, and external walls and wooden or concrete floors with wooden beams, as a striking example with a risk of interstitial condensation and decay. In tropical regions the risks of building decay from thermal bridges is somewhat smaller

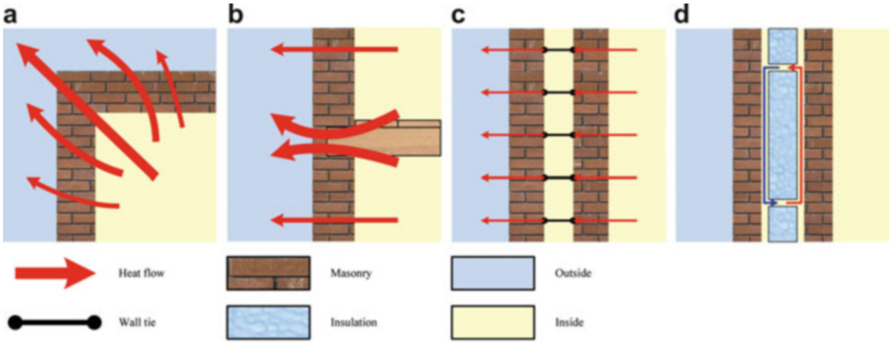


**Fig. 7.12** Four types of thermal bridges can be identified: (**a**) geometrical, (**b**) structural, (**c**) systematic and (**d**) convective

but increased heat transfer and increased indoor surface temperature are still present. Thermal bridges can be categorized into four groups (Olsen and Radisch 2002):

- Geometrical thermal bridges;
- Structural thermal bridges;
- Systematic thermal bridges;
- Convective thermal bridges.

Geometrical thermal bridges (Fig. 7.12a) are cold bridges formed by geometrical aspects i.e. dimensional changes, which increases the heat emission or absorbing surface area. Examples are inner or outer corners (3D thermal bridges) or room edges (2D thermal bridges) of external partitions. Structural thermal bridges (Fig. 7.12b) are formed by deliberate penetrations of the building envelope. Examples are wooden beams and concrete slabs passing through the building fabric. Systematic thermal bridges (Fig. 7.12c) are thermal bridges that are repeated in a specific pattern. Examples are wooden beams of floors or wall ties in cavity walls. Convective thermal bridges (Fig. 7.12d) are formed by air flow, due to e.g. air leakages and penetration of pipes through structural elements. Obviously, in practice one can also find combinations of these.

It is not easy to study thermal bridges in practice, but computer modeling generally provides an efficient alternative. The input of dimensions, material properties and temperature gradients generates a two or three dimensional visualization of the gradients formed inside the structure. An example of this type of modeling is shown in Fig. 7.13.

It is obvious that by adding insulation to the inside, the floor will become colder. Outdoor temperatures will determine the risk of rot due to high relative humidities at the beam end (Morelli et al. 2010; Tersteeg 2009), as can be seen in Fig. 7.14.

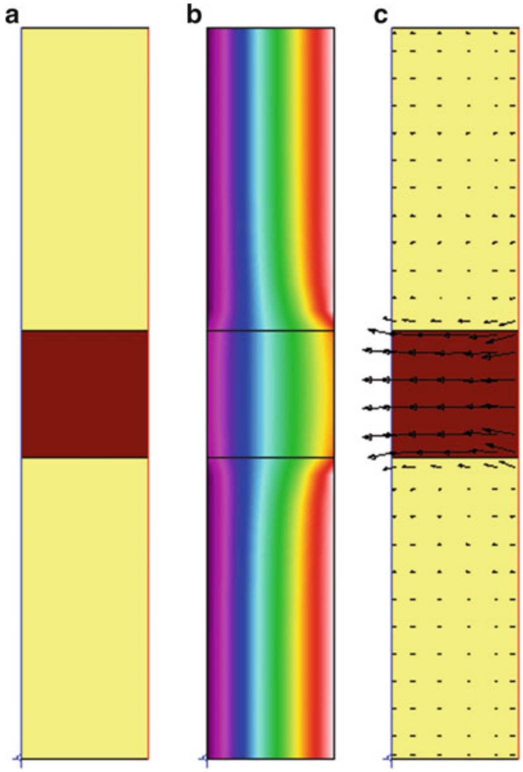


**Fig. 7.13** A typical example to illustrate the effect of thermal bridges: (**a**) a 30 cm wall built up that consists of a high thermal insulator (mineral wool, *yellow*) around a low thermal insulator (brick, *brown*), (**b**) isotherms of the structure as a result of an outdoor temperature of 0 °C and an indoor temperature of 20 °C, (**c**) heat flux through the wall as a result of an outdoor temperature of 0 °C and an indoor temperature of 20 °C. Image (**b**) shows the outdoor surface temperature near the thermal bridge is higher than the surrounding surface temperature and the indoor surface temperature is lower than the surrounding indoor temperature. In image (**c**) the heat flux through the thermal bridges is higher that the surrounding wall

Many modelling studies have been performed to determine the optimal thickness of the insulation layer and the likelihood of thermal bridges (Song and Kim 1997; Schellen et al. 2008). For the restoration of the Rijksmuseum in Amsterdam a two dimensional hygrothermal model study was done by the Dresden University of Technology to analyze the hygrothermal effects of two internal insulation options for the external walls using cellular glass or calcium silicate (Häupl et al. 2005; Häupl 2007). It was concluded that a thickness of 35 mm calcium silicate is optimal. A thicker layer of 50 mm or the use of foam glass would increase the build-up of moisture inside the wall.

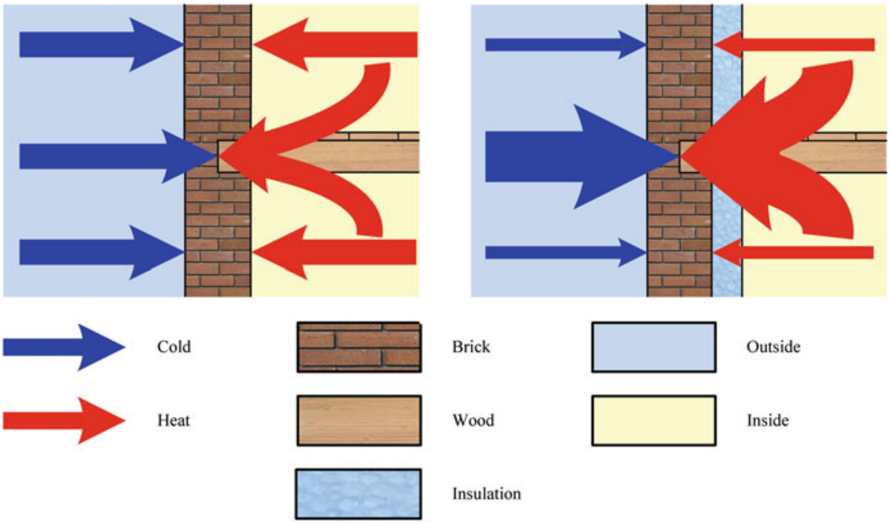


**Fig. 7.14** Example of a wooden beam and wooden floor imposed in a masonry wall with and without insulation. Due to the inside insulation the heat flux through the wall deceases, while the heat flux through the beam end increases, making the area colder creating a thermal bridge

### *7.3.4 Thermal Mass*

Massive buildings generally have large thermal mass or thermal inertia. This means that they are capable of storing thermal energy. The thermal mass depends on the specific density (symbol: $\rho$, unit: $kg/m^3$) and the specific heat capacity (symbol: c, unit: kJ/kg) of the building materials used. The higher the density or heat capacity, the higher the thermal mass. Thermal mass can be very beneficial to control the indoor climate because low winter temperatures are stored and will subsequently make the indoor climate colder during summer and vice versa. This effect can be nicely experienced when visiting a relatively cold church or bunker during a warm summer day. But even materials with high thermal mass become useless as a thermal buffer when the rate at which heat is absorbed or desorbed is too fast, or too slow. For materials this property depends not only on the density and heat capacity but also on the thermal conductivity (symbol: $\lambda$, unit: W/mK). The rate at which heat will adsorb or desorb is given by the thermal diffusivity (symbol: $D_T$, unit: $m^2/s$). The effective depth is a measure for the thickness of the wall that is actually effective to buffer the temperature. This effective depth depends on the thermal diffusivity and the length of a certain periodical fluctuation. The thermal buffer capacity is the product of the thermal mass and the effective depth. A very thin material will simply not have sufficient storage capacity and will therefore have a low thermal buffer capacity. A material which has a large thermal storage capacity but is a bad thermal conductor, i.e. low thermal diffusivity, will heat up and cool down too slowly for this property to be useful and vice versa. Their mutual

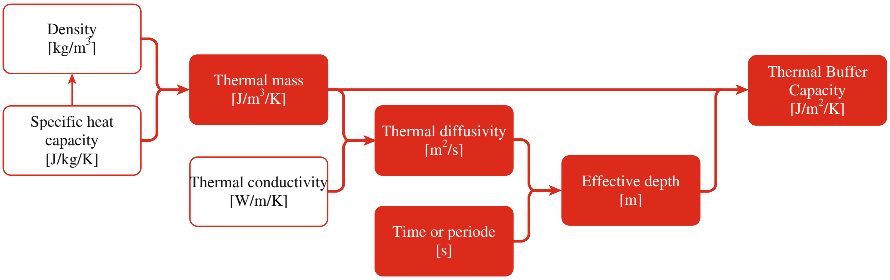


**Fig. 7.15** The relationship between thermal properties (*solid boxes*) of building materials, the thermal buffer capacity and the derived physical quantities

**Table 7.5** Effective depth calculated for different periods and building materials

| Material | Period t [h] | Density ρ [kg/m$^3$] | Storage capacity c [J/kg/K] | Conductivity λ [W/K/m] | Effective depth d* [cm] | Thermal buffer capacity [kJ/m$^2$/K] |
|---|---|---|---|---|---|---|
| Concrete | 24 | 2500 | 840 | 2 | 16.2 | 339.9 |
| Concrete | 2160 | 2500 | 840 | 2 | 153.5 | 3,224.2 |
| Brick | 24 | 1900 | 840 | 0.7 | 11.0 | 175.3 |
| Lime plaster | 24 | 1600 | 840 | 0.95 | 13.9 | 187.4 |
| Wood | 24 | 800 | 1880 | 0.17 | 5.6 | 83.9 |
| Mineral wool | 24 | 100 | 840 | 0.04 | 11.4 | 9.6 |

relationships are presented in Fig. 7.15. In general, the higher the thermal conductivity the higher the effective depth and the better the overall thermal buffering performance.

In Table 7.5 the effective depth is given for different building materials when submitted to a for a 24 h cycle. For concrete also a 3 month (2160 h) cycle is provided. The 3 month cycle shows that slow fluctuations will penetrate deeper into the building fabric. The effective depth for concrete for the diurnal and 3 month cycle are respectively 6.2 cm and to 153.5 cm. This means that the complete buffering of a 3 months cycle would require a thickness of 1.5 m of concrete. This may be found in bunkers but generally not in traditional buildings. On the other hand for the other materials the buffering of daily cycles only a thickness varying from 5.6 to 16.2 cm is needed, which can be found in most buildings. As can be seen from Table 7.5 concrete, brick and lime plaster are good thermal buffers (high thermal buffer capacity). It should be noted that when the practical available depth is smaller than the theoretical effective depth, the thermal buffer capacity will be the product of the thermal mass and the available depth.

The effect of a high thermal mass on the indoor climate is that in regions with considerable temperature difference between seasons, massive buildings tend to be cooler in summer and warmer in winter. This effect can be experienced in massive buildings such as churches, bunkers and castles in the northern hemisphere. As a practical consequence seasonal fluctuations are buffered to a lesser extent than diurnal fluctuations. Even though the wall thickness is generally too small for full seasonal buffering, most massive buildings in the Northern hemisphere still have sufficient thermal mass to reduce seasonal indoor (surface)temperature fluctuations and reduce the need for heating and cooling.

In regions with a more or less constant outdoor temperature throughout the year, such as the tropical regions thermal mass will result in a very stable, but high indoor temperature close to the outside temperature. These temperatures generally are too high for thermal comfort during both day and night. Therefore traditional buildings in those regions tend to be light weight, i.e. low mass and highly ventilated, to allow cool air to enter at night (Cairns Regional Council 2011).

In Fig. 7.16 the effect of the thickness of a brick wall, on the indoor surface temperature is plotted. The graph shows the indoor surface temperature for a 0.22 m (orange line) and a 0.44 m (red line) thick masonry wall. The indoor surface temperature is more or less constant at 24 °C (75 °F), while the outdoor temperature (brown line) and the solar radiation (yellow line) show large fluctuations. It can be seen that surface temperature fluctuations of the 0.44 m thick wall are smaller and shifted 3 h compared to those of the 0.22 m thick wall. This is the effect of a higher thermal storage capacity. Furthermore, the average indoor surface temperature of the 0.44 m thick wall is about 0.8 °C (1.4 °F) lower, compared to the 0.22 m thick wall. In Fig. 7.16 only diurnal temperature fluctuations are considered but for long-term fluctuations, such as seasonal fluctuations, the effect will be very similar.

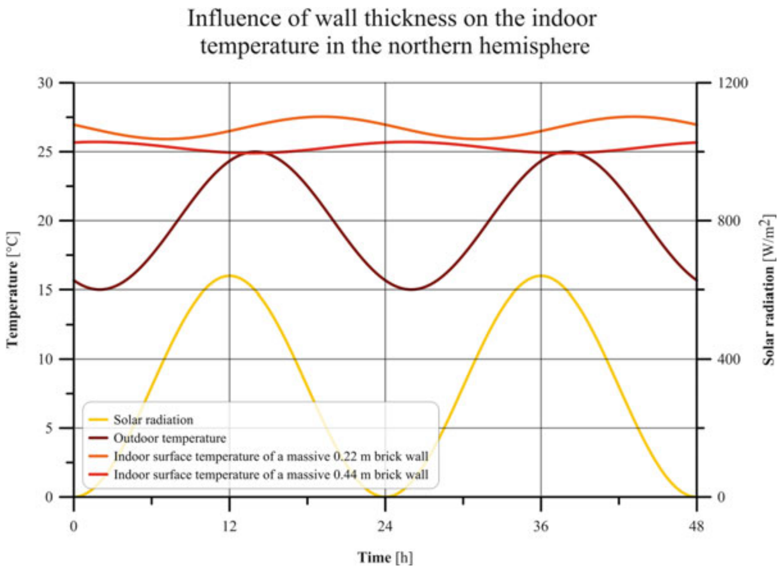


**Fig. 7.16** Calculated indoor surface temperatures for a thick wall, i.e. large thermal mass and a thin wall, i.e. low thermal mass (Based on data from Tammes and Vos 1984)

For thermal mass to be effective, the storage capacity should be considerable and accessible. Considerable means that the material needs to have a fairly high density and a fairly high thermal capacity so it can absorb thermal energy. When thermal mass is in contact with the indoor climate it is accessible and useable. Sometimes alterations like thermal insulation will block access to the thermal mass, thus reducing the potential of the thermal mass considerably.

The diurnal effect of thermal mass is illustrated in Fig. 7.17. During winter, when the outdoor air is colder than indoors, thermal mass can be heated by solar radiation (Fig. 7.17a) and the building gains thermal energy, which is re-radiated into the room during the night (Fig. 7.17b).

In summer (Fig. 7.18) it is more effective to prevent warming up of thermal mass, e.g.by using sun blinds such as shutters and sunshades on the outside during the day. Heated outside air will exchange heat with the thermal mass (Fig. 7.18a). During the night this heat can be released by ventilation to the relatively cold night air and removed from the room (Fig. 7.18b). This is why in Mediterranean countries

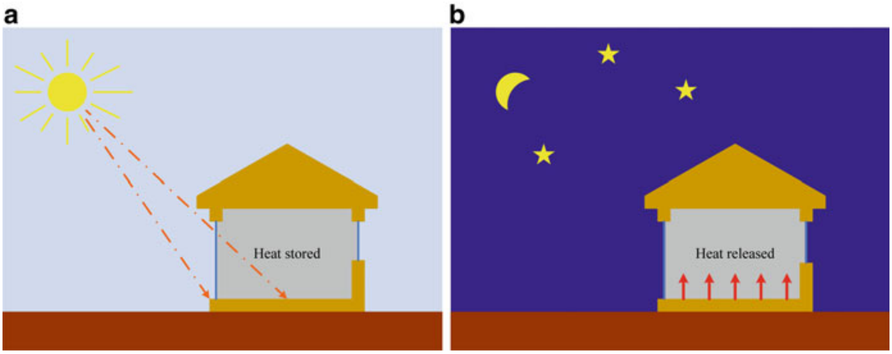


**Fig. 7.17** A schematic representation of the concept of thermal mass in winter during day (**a**) and night (**b**) (Taken from: Department of Industries 2014)

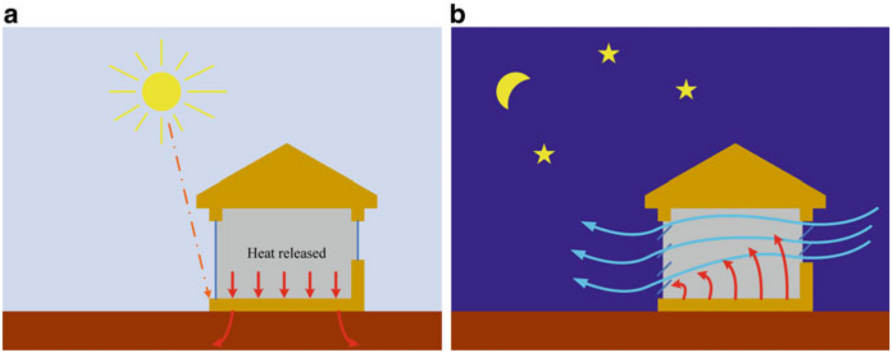


**Fig. 7.18** A schematic representation of the concept of thermal mass in the summer during day (**a**) and night (**b**) (Taken from: Department of Industries 2014)

**Fig. 7.19** Two buildings in Olinda, Brazil with different types of sun barriers: (**a**) a dwelling with closed windows (shutters) and doors during daytime and (**b**) a church window where the glazing system has additional shutters placed to the inside of the building and thus decreasing the sunlit area

**Table 7.6** Thermal properties of the two selected vertical envelope constructions (Ferrari 2007)

| Type | U-value [W/m$^2$ K] | R$_c$-value [m$^2$K/W] | Heat capacity [kJ/m$^2$K] | Thickness (excl. plaster) [cm] |
|---|---|---|---|---|
| Heavy | 0.66 | 1.35 | 1,482.2 | 95 |
| Light | 0.66 | 1.35 | 47.3 | 6 |

shutters and windows are closed during the day and opened for maximum ventilation during the night. In tropical regions thermal mass plays only a small role in the daily cycles, since the temperature fluctuations are generally too small.

For thermal mass to be effective, temperature differences larger than 6 °C (11 °F) between day and night are generally required (Department of Industries 2014). If the temperature fluctuations are smaller, the temperature in the building will be about the same indoors as outdoors. For temperature differences larger than 10 °C (18 °F) high mass constructions are desirable (Department of Industries 2014). In tropical climates with small diurnal fluctuations, high mass constructions can cause thermal discomfort. The amount of energy stored during the day and released at night, keeps the indoor temperatures at high levels. Careful design of thermal mass, shading devices and insulation layers can overcome these problems, see Fig. 7.19a, b.

Ferrari (2007) presents the effectiveness of thermal mass on the reduction of energy demand. Two vertical envelope constructions were modelled: heavy and light (Table 7.6), with the same overall heat transfer coefficient.

For both constructions, the energy demand was calculated by simulation. The DOE-2 program was used to predict the hourly energy use and energy cost of the building using hourly weather information and a description of the building and its HVAC equipment and utility rate structure. Several variables were simulated: building typology (1 story, 2 stories, 4 stories and 16 stories), different climate scenario's (Rome, Milan and Palermo, Italy), different azimuths (south, west, north, east). In all the different scenarios, the overall conclusion was similar to the base case: the heavy construction was more energy efficient in both summer and winter (Fig. 7.20).

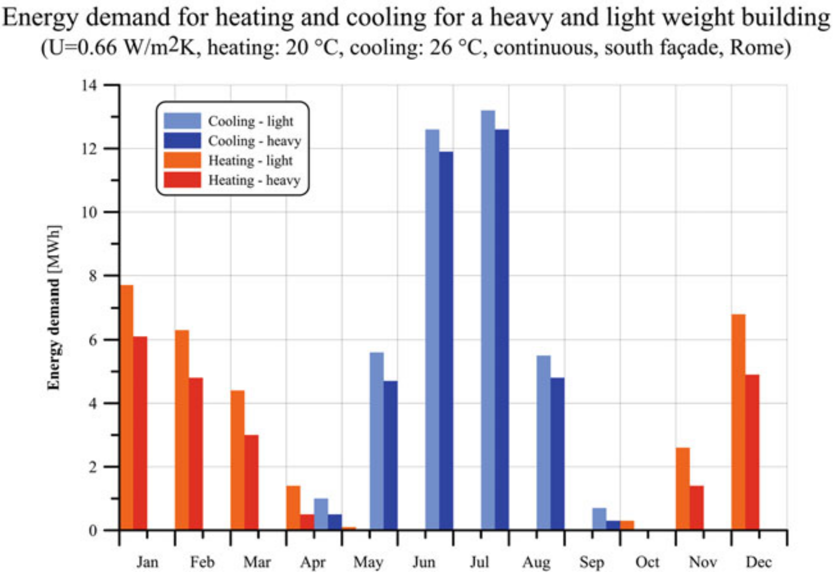


**Fig. 7.20** Comparison of the energy demand for a light and heavy building envelope (Taken from: Ferrari 2007)

**Special: Roofs in the Tropics**

In tropical regions there are two strategies to maintain indoor temperatures at comfortable levels. The first is to reduce the infiltration of warm outside air by making the building airtight and adding a cooling system. This is an energy consuming way to control the indoor temperature. One of the positive side effects of cooling the indoor air, is dehumidification. A less energy consuming way to maintain acceptable indoor temperatures, is to use building materials and structures to control natural ventilation. First of all the influence of the sun needs to be limited. This means that windows on the east and west side need to be shaded or avoided and that heat transfer through the roof needs to be limited by insulation, preferably on the outside. The effect of insulating a concrete roof on the indoor temperature was investigated by Halwatura and Jayasinghe (2008). The research showed that an uninsulated concrete slab of 125 mm thickness (Fig. 7.21) can generate indoor surface temperatures higher than 40 °C (104 °F), which will be uncomfortable to people. Insulating the concrete slab on the outside reduces surface temperatures by approximately 10 °C (18 °F).

(continued)

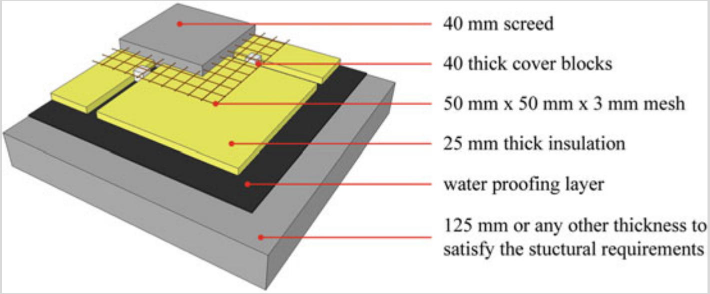


**Fig. 7.21** Cross section of the concrete roof investigated by Halwatura and Jayasinghe (Drawing adapted from Halwatura and Jayasinghe (2008))

If altering the building and/or implementation of an HVAC-system are not possible, then ventilation remains the only option. This can also help to remove excess heat and reduce relative humidities to a certain extent.

### Special: Dew Point and Condensation

In the Northern hemisphere, when outside temperatures are very low, condensation on the inside of windows panes can often be observed in rooms with a high moisture load, such as kitchens, bathrooms and sometimes even historic houses and museums.

When the surface temperature is low enough, water vapor in the boundary layer will condense to become liquid water: the relative humidity near the surface is 100 %. The temperature at which condensation occurs is the *dew point temperature* ($T_d$). For every combination of temperature and relative humidity there is a corresponding dew point temperature. The dew point temperature at 20 °C (68 °F) and a relative humidity of 50 % is approximately 9.3 °C (49 °F). So when the surface temperature drops below 9.3 °C, condensation will occur (Special: the psychrometric chart). In hot and humid climates the dew point temperature is much higher. At 75 % relative humidity and 30 °C (87 °F) the dew point temperature is 26 °C (78 °F). There are several dew point calculators available on the internet that can be used by providing the relative humidity and temperature.

In Fig. 7.22 a wooden window is shown with two panes of single glass. The window on the left contains single glazing without any coating and has no condensation. The window on the right is also single glazing but with a low emissive coating on the inside. The coating increases the thermal resistance of the boundary layer. Therefore less heat from the inside is lost through the window to the outside. The outisde temperature reduces the surface temperature of the glazing below the dew point temperature and surface condensation occurs. The outdoor and indoor climate conditions are the same for both windows.

(continued)

**Fig. 7.22** Two window panes in a wooden window frame. The *left* window is a single clear pane. The *right* window pane is made of single clear glass coated with a low emissive metal oxide coating on the inside (Photo: H. Schuit 2013)

Notice that due to this process the air is dehumidified. In the presence of moisture sources, such as humidifiers, this process will continue. However, in the absence of a moisture source, condensation might stop due to a decrease of absolute humidity, with a subsequent decrease of the indoor relative humidity and thus a decrease of the dew point temperature. Having lowered the absolute humidity in the air, condensation is less likely to reoccur, if the temperature remains the same.

## 7.4 Air

Air or air flow is a way to transfer thermal energy or water vapor from one place to another. Air flow can be quite fast and can hold a significant amount of thermal energy or water vapor. Air flow can also be quite complex. Measurements have shown that the air flow in a corridor of an office building was occurring in two opposite directions at same time. Also the mixing of air can sometimes be complex. Air flow patterns can be visualized by smoke or simulation but can give only a rough indication of relatively large air flows. Knowledge of the driving forces will help understand the most common air flow patterns. This will also help in comprehending the way the indoor climate is formed and influenced (Fig. 7.23). The exchange of air between different zones, i.e. outside versus inside, or room versus staircase, is called the air exchange rate (AER). The AER expresses the total amount of infiltration,

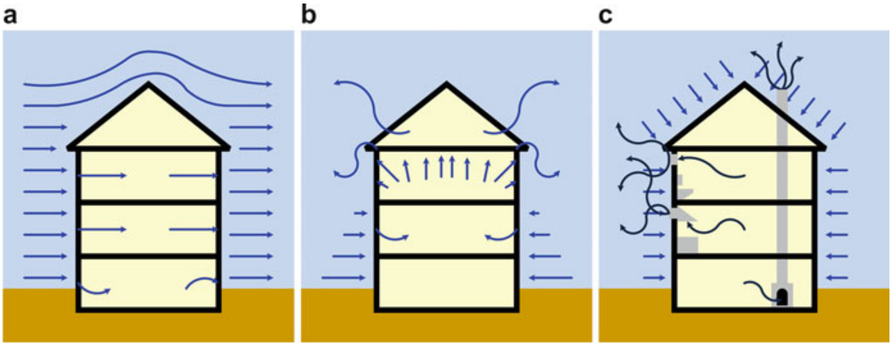


**Fig. 7.23** Causes of air flow through a building (**a**) wind, (**b**) stack effect, (**c**) ventilation systems

exfiltration and ventilation of a given zone. The AER is defined as the amount of times a given volume is exchanged per unit time (day or hour).

## *7.4.1 Infiltration*

Infiltration is the uncontrolled exchange of air between zones. It is caused by wind, negative pressurization of the building, and by air buoyancy forces, known more commonly as the stack effect. The pressure differences between the windward side and leeward side of a building will cause an air flow through the building. On the windward, i.e. the high pressure side air will enter the building through cracks and seams (Fig. 7.23a) and will leave on the leeward, i.e. the low pressure side of the building.

When a building is heated, the density of the air is reduced and it will rise. This will create a high-pressure area near the roof of the building, causing air to escape through seams and cracks at the upper levels. At ground level, a low-pressure area is formed, which will create air flows into the building (Fig. 7.23b). Obviously, exfiltration is the opposite of infiltration and describes the uncontrolled exchange of indoor air to the outside.

## *7.4.2 Ventilation*

Ventilation is the controlled exchange of air between indoors and outdoors, or between different zones indoors. Ventilation can be divided into natural ventilation, which describes the passive process of opening doors and windows, and mechanical ventilation by means of active systems using one or more fans. The main purpose of ventilation is to supply a sufficient amount of fresh air to the people within a building, and to remove pollutants and excess moisture and smells from the building (Rode 2005).

Buildings with chimneys and appliances for air ventilation will generate an air flow due to a low indoor pressure. Open chimneys and fireplaces are very effective in transporting air via stack pressure. This air is replaced by outdoor air that enters into the building through seams, cracks and other openings (Fig. 7.23c).

### 7.4.3 Air Flow

Air flow with a certain temperature holds a specific amount of thermal energy. This amount depends on the temperature difference (symbol: $\Delta T$ or $\Delta\theta$, unit: °C, °F or K), the density (symbol: $\rho$, unit: kg/m$^3$) and thermal heat capacity (symbol: c, unit: kJ/kg) of the air. The density of air at 20 °C (68 °F) is about 1.2 kg/m$^3$ with a heat capacity of 1,000 kJ/kg. For practical reasons these are usually assumed to be constant. The loss or gain of energy due to ventilation or infiltration has to be compensated when a more or less constant indoor climate is required. The higher the airflow rate, the more energy is lost or gained. This will determine the necessary capacity of heating, cooling, humidification and dehumidification. Therefore it is very helpful to know the amount of air that is exchanged with the outside, i.e. the air exchange rate (AER).

Assessing the AER for a closed zone seems relatively straightforward, but in practice adjoining rooms will exchange air, due to wind effects the building will allow some air to be exchanged with the outside and air is actively exchanged by an HVAC system making the real situation often quite complicated. The multitude of air exchanges are visualized in Fig. 7.24. Note that infiltration and exfiltration can

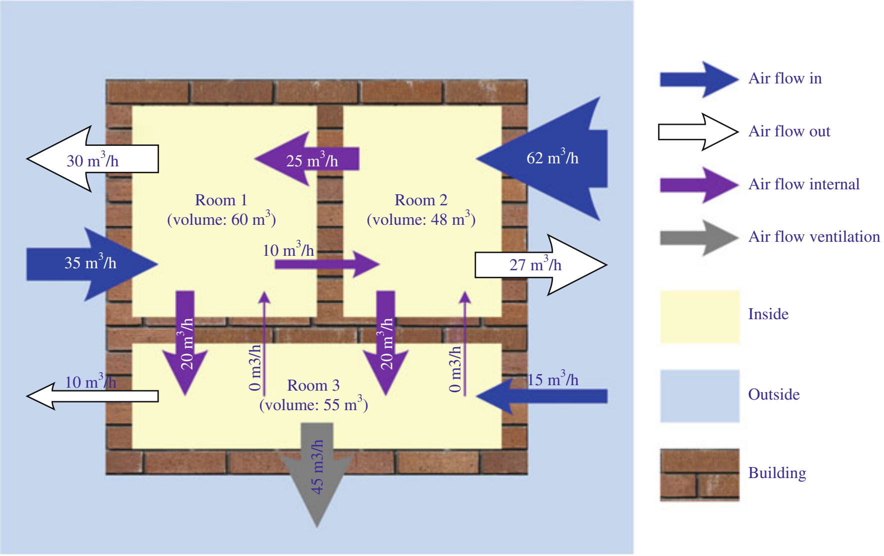


**Fig. 7.24** A schematic representation of air exchanges for a fictional building. The *arrows* indicate the direction of air flow and the numbers the amount of air moved

take place simultaneously between the in- and outside but also between internal zones. Internal air flows can change rapidly due to outside conditions like wind and stack pressure.

To assess the air flow within a zone there are two basic rules:

1. The amount of air entering the building must be equal to the amount of air leaving the building, and
2. The air entering a zone must be equal to the amount of air leaving a zone.

The air flow in $m^3$/h can be determined by measuring the air velocity (m/s) over a certain surface ($m^2$). Practically this involves measuring air velocities at all openings in a zone and determining the size of these openings and multiplying them. The total flow rate is than calculated as the sum of all individual flow rates for each opening.

When in equilibrium the amount of air entering must be equal to the amount of air leaving, see Fig. 7.24. Thus: air flow in, equals air flow out. It can be seen that the amount of air entering for room 1, equals 35 + 0 + 25 = 60 $mm^3$ of air per hour. Similarly, the amount of air leaving equals 30 + 20 + 10 = 60 $mm^3$ of air per hour. Since the volume of the room is 60 m3 the AER is 1 per hour. Please note that the air flow from room 3 to room 1 (and from room 3 to room 2) is zero. This indicates that room 3 is depressurized and as we can see in Fig. 7.24 this is done by a mechanical ventilation system (grey arrow). What applies to room 1 must also apply to room 2 and 3 and to the building as a whole.

Most buildings are not air tight, especially historic buildings can be very leaky due to seams and cracks in the building envelope. To design an HVAC-system, the amount of air that needs to be climatised depends directly on the air tightness of a building. So the AER of the building must be known. Otherwise the subtle balance between air in (ventilation plus infiltration) and air out (exfiltration) can easily be disturbed by wind effects and the climatic specifications might never be met. But to achieve satisfactory air tightness, large alterations of the (historic) building envelope might be necessary, with subsequent loss of historic, architectural and cultural values.

Changing the air exchange of a building (zone) will have an impact on the moisture balance and the amount of fresh air brought in from outside. In Northern regions the building accumulates moisture from driving rain and ground water, this moisture will evaporate on the out- and inside of the building. When these buildings are insulated and made more airtight, not only the heat loss by conduction (transmission) and convection (ventilation) is reduced, but also the infiltration of outside air and therefore the ability of the building to remove moisture. Changing the historic moisture balance might reduce risks in the short term, but if done improperly it can also increase the risk of mold significantly.

## 7.5 Moisture

As illustrated in Fig. 7.1 the indoor climate is influenced by external and internal moisture sources. Generally rainwater is the most significant and influential external moisture source. Failure of the drainage system will cause wetting of walls, and subsequent evaporation to the inside might lead to e.g. mold and/or salt damage. Lack of maintenance is often the cause for failure of drainage systems, but other causes could be:

1. Debris, leaves and moss in parapet and central gutters;
2. Damaged lead or asphalt gutters;
3. Missing or loose mortar joints between ridge tiles;
4. Displaced or damaged slates;
5. Gaps in lead flashings at abutments, chimney stacks and parapets;
6. Cracks or missing mortar joints on top surfaces of coping stones and parapets;
7. Open joints in brickwork;
8. Structural movement e.g. opening of mortar joints;
9. Damaged and under-sized rainwater gutters and downpipes;
10. Hairline cracks in render;
11. Missing render;
12. Plant growth and debris in gutters and gulley's;
13. Higher external ground level.

In order to prevent water from entering the building, regular maintenance is essential. Best practice is to make annual inspections and plan future maintenance in advance. Obviously, the risk of water entering the building depends on the amount of rainfall and the capacity of the drainage system. The amount of precipitation depends on the geographical location and orientation. In Fig. 7.25 the average annual amount of precipitation is given in inches and centimeters for any location in the world. Regions with high precipitation, e.g. due to rainy seasons, should take measures to avoid excess of water entering the building and to ensure water drains away from the building fabric.

Some rainwater is absorbed by the ground. Foundations below the groundwater level will absorb and transport this water by capillary suction. As soon as the

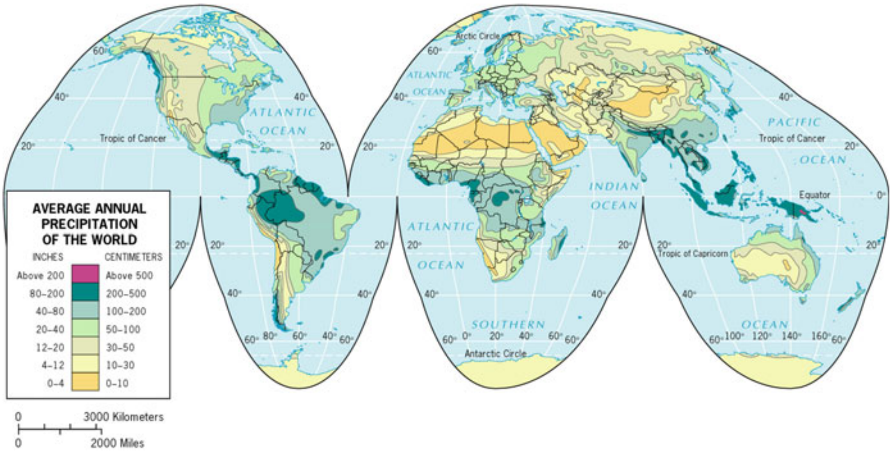


**Fig. 7.25** Average annual precipitation of the world (Source: http://planetolog.com)

environmental conditions are suitable for drying, in general a low relative humidity, liquid water in the building material will evaporate at the surface to become water vapor. As long as the water source is infinite, like groundwater, there will be an equilibrium (see Fig. 7.32). Whether or not this will lead to building decay depends on the materials used and the exterior and interior finishes as described in Chap. 5.

Equipment can be used to change the indoor relative humidity. In humid climates dehumidification might be necessary. Dehumidification will extract water vapor from the indoor climate by condensation on a cold surface, see Chap. 9. Increasing ventilation with dry outside air, i.e. outside air with a lower absolute humidity than the indoor air (Fig. 7.26) or increasing the indoor temperature are options to reduce the relative humidity. The latter might be energy consuming and increases the risk of chemical degradation and lower thermal comfort at high temperatures.

In dry climates humidification might be needed. Humidification will add water vapor to the indoor climate by evaporating water. In Chap. 9 options to increase the relative humidity are discussed. Some indoor activities will also generate moisture. Visitors will exhale wetted air and when in great numbers might even change the absolute humidity. During a wedding at Our Lord in the Attic the absolute humidity increased from 8 to 10 g/kg due to the attendance of 100 people (Maekawa et al. 2007). The capacity of some typical moisture sources, found in homes are provided in Table 7.7.

In some cases the outdoor climate can be used as a moisture source or sink. This depends on two factors: First the actual indoor relative humidity is not the desired indoor relative humidity and secondly, the outdoor absolute humidity needs to be

**Fig. 7.26** Sometimes ventilation is an easy, cheap and sustainable way to cool and dry the indoor air in tropical regions

**Table 7.7** The typical moisture capacity of some indoor sources

| Source | Typical moisture capacity | |
|---|---|---|
| Cooking | 2.0 l | At a time |
| Dishwasher | 0.5 l | Per use |
| Showering | 0.5 l | Per use |
| Plants | 1.0 l | Per day (average) |
| Dryer | 3.5 l | At a time (after centrifugation) |
| People | 0.25–0.50 l | Per person per hour |

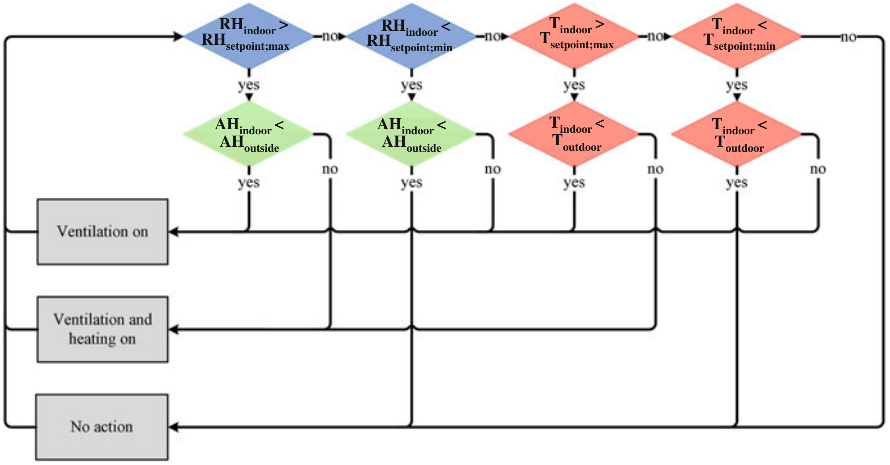


**Fig. 7.27** Schematic representation of the ventilation control system for 'smart' ventilation (Taken from: Peters 2007)

higher than the indoor absolute humidity, if the indoor relative humidity is too low, and vice versa. This concept is called smart ventilation. For Museum Muiderslot in the Netherlands this strategy (Fig. 7.27) was successfully used to improve the indoor climate. Although the indoor climate sometimes still fell outside the climate specifications of 5 °C $<$ T $<$ 25 °C (41 °F $<$ T $<$ 77 °F) and 40 % $<$ RH $<$ 65 % (±10 %/day). In winter the indoor climate fell within the specifications 69 % of the time instead of 25 % and in summer 83 % instead of 49 % (Peters 2007).

Moisture, both as a liquid or as a gaseous vapor can be damaging to the building fabric. When the moisture content of a building material is high for a long period of time the risk of mold or rot increases significantly. In cold climates high moisture loads of the building envelope will also increase the risk of frost damage. But even when a building is designed to prevent water from entering, some moisture will be transported into the building; by diffusion of water vapor and capillary suction of liquid water. To successfully mitigate water accumulation within the building and its fabric some knowledge on the moisture transport mechanism is essential. For a good understanding of moisture transport mechanisms it is important to know whether liquid water or its vapor is involved. The driving forces behind the transport mechanisms are different, see Table 7.8.

**Table 7.8** Driving forces behind the transportation of moisture

| State of aggregation | Mechanism | Driving force |
|---|---|---|
| Water vapor | Diffusion | Difference in partial vapor pressure |
| | Convection | Difference in total air pressure |
| Water | Capillary | Difference in capillary suction |
| | Gravity | Mass |
| | Pressure | Difference in total external air pressure |

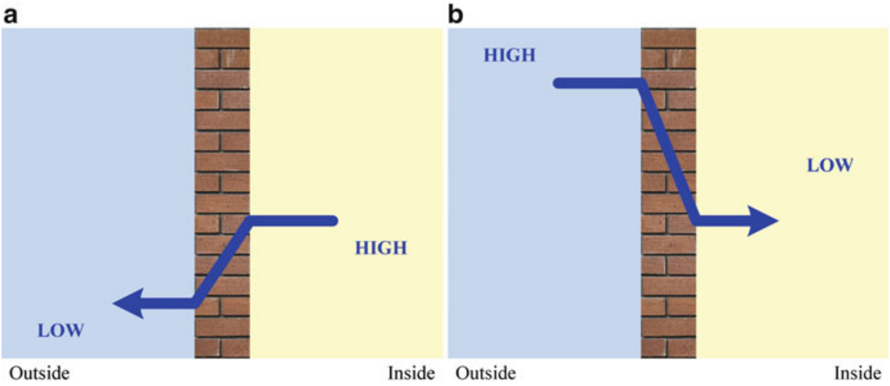


**Fig. 7.28** A schematic representation of vapor diffusion through a wall in the northern hemisphere in winter (**a**) and summer (**b**)

## 7.5.1 *Vapor Transport by Diffusion*

The driving force of vapor diffusion is the partial pressure differences of water vapor. Note that this pressure difference only refers to the water vapor and thus is related to the absolute humidity of the air. Water vapor will move from areas with high water vapor pressure, i.e. high absolute humidity, to areas with low vapor pressure.

A museum with an indoor relative humidity of 50 % and a temperature of 20 °C (68 °F) will have an absolute humidity of 8.66 g/m$^3$. The partial water vapor pressure will be about 1,170 Pa. During cold periods in the northern hemisphere low outside temperatures, e.g. −5 °C (23 °F) and a relative humidity of about 85 % will result in an absolute humidity of 2.91 g/m$^3$. The partial vapor pressure will then be about 340 Pa. As a result moisture will flow from the inside to the outside, see Fig. 7.28a. In summer with temperatures of 30 °C (86 °F) and 70 % relative humidity outside, the absolute humidity will be 21.3 g/m$^3$ and the partial water vapor pressure will be about 3,190 Pa. The water vapor will flow from the outside to the inside, see Fig. 7.28b. Note that the partial pressure difference for water vapor in summer is significantly larger than in winter. Resulting in a larger moisture flow in summer.

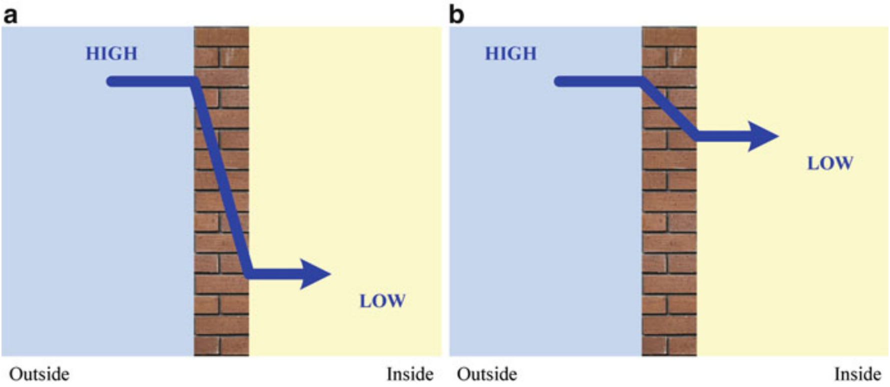


**Fig. 7.29** A schematic representation of vapor diffusion through a wall in the tropical region in wet season (**a**) and dry season (**b**)

If the building is located in a tropical region the situation is slightly different. Outdoor temperatures will be high. In the wet season the outdoor temperature decreases a little e.g. to 27 °C (81 °F) but the relative humidity will increase to 80 or 90 %. The absolute humidity will be somewhat higher: 19.5 g/kg. The water vapor pressure will be around 3000 Pa. The indoor temperature can be estimated and will be lower than outdoors: 24 °C (75 °F). The indoor relative humidity decreases to 55–65 %. The absolute humidity will be around 11.5 g/kg and the water vapor pressure will be around 1,800 Pa. Water vapor will flow from the outside to the inside, see Fig. 7.29a. During the dry season, outdoor temperatures of around 30 °C (86 °F) and a relative humidity of around 70–80 % can be measured. The absolute humidity would be around 20.5 g/kg and the water vapor pressure would be around 2,900 Pa. Indoor conditions for traditional buildings can be estimated for the dry season with an indoor temperature of around 27 °C (81 °F) and relative humidity of around 72 %. The absolute humidity would be around 16.4 g/kg and the water vapor pressure would be around 2,600 Pa. Water vapor will still flow from the outside into the building, see Fig. 7.29b.

One of the key factors that determine the rate in which vapor diffuses through materials is the water vapor resistance factor (abbreviated as wvrf, symbol: μ, unit: dimensionless ratio). This factor characterizes the resistance of materials to vapor transport compared to one meter of air, which is indexed as 1. This μ-value is relative and helps to indicate the relative water vapor permeability of different materials. Materials with vapor barrier characteristics that reduce vapor diffusion obviously have very high numbers, ranging from 9,000 to 150,000 (see Sect. 7.5.3). Metals, glass and cellular glass insulation are vapor and watertight. In Table 7.9 some wvrf's are provided for some common building materials.

**Table 7.9** Water vapor resistance factor (wvrf) of different building materials

| Material | | Wvrf |
|---|---|---|
| Insulation material | Mineral wool and capillary active panels | 1–6 |
| | Petro chemicals (PS, PUR, PVC, etc.) | 15–250 |
| | Foamglas | ∞ |
| Gypsum board | | 5–6 |
| Plaster | | 6 |
| Brick | | 9–13 |
| Concrete | | 25–33 |
| Wood | | 100 |
| Glass | | ∞ |
| Metals | | ∞ |

### *7.5.2 Vapor Transport by Convection*

Convective vapor transport is in many cases the most important cause of moisture related damage in the northern hemisphere (Janssens and Hens 2003; Rousseau 2003; Said et al. 2003). In cold climate regions the building envelope has a low temperature during winter. When warm, humid indoor air is allowed to penetrate into the building envelope, the water vapor will condensate inside the construction. There are several pathways that can lead to surface condensation as can be seen in Fig. 7.30.

In winter the building envelope in the northern hemisphere becomes colder moving from inside to the outside. Especially when buildings are insulated on the inside, or when the cavity is filled with an insulation material, the outer leaf of the building envelope will get colder increasing the risk of surface condensation. So, once warm humid indoor air penetrates the building envelope it will cool the air down. As a result water vapor will condense on, or inside, the building structure, known as surface condensation.

Vapor diffusion through materials plays a minor role when compared to convective vapor transport. The amounts of moisture transported by convection typically far exceeds those of diffusion (Anonymous 1997). Convective moisture transport is driven by the difference in total air pressure (see Sect. 7.4: Air), which is primarily related to the air tightness of the zone.

### *7.5.3 Water Transport by Capillary Sorption*

Materials that allow moisture transport are referred to as being hygroscopic. These materials have pores with a wide range of sizes. The smaller the pore size, the larger the capillary suction. Furthermore small pores can absorb water from large pores but not the other way around. Pores can be classified by size as micro-pores

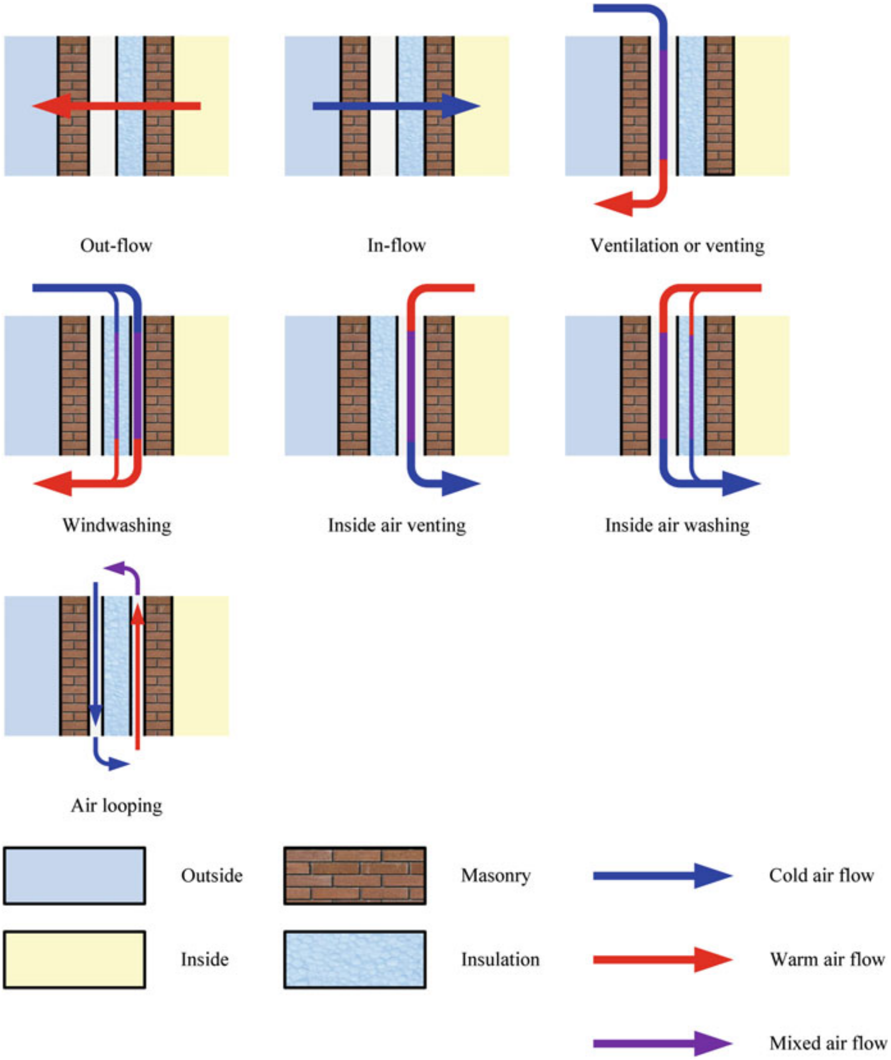


**Fig. 7.30** Different air flow modes in cavity walls. If warm humid air (*red*) penetrates the structure it will cool off (*purple*). If the temperature of the cold air (*blue*) drops below dew point condensation will occur (Taken from: Hens et al. 2007)

(diameter <10 nm), meso-pores (diameter between 10 and 100 nm) and macro-pores (diameter larger than 100 nm) (Van Hees and Lubelli 2012). Most materials will have both large and small pores. Large pores have a radius of 1–100 μm, small pores have a radius of 0.01–1 μm (Fig. 7.31).

When a material is wetted, the large pores quickly absorb water, while small pores take more time to be filled. The drying rate of large pores is obviously also quicker than the small pores. The pore size distribution determines the wetting and drying behavior of a material. The most important water transport by capillary

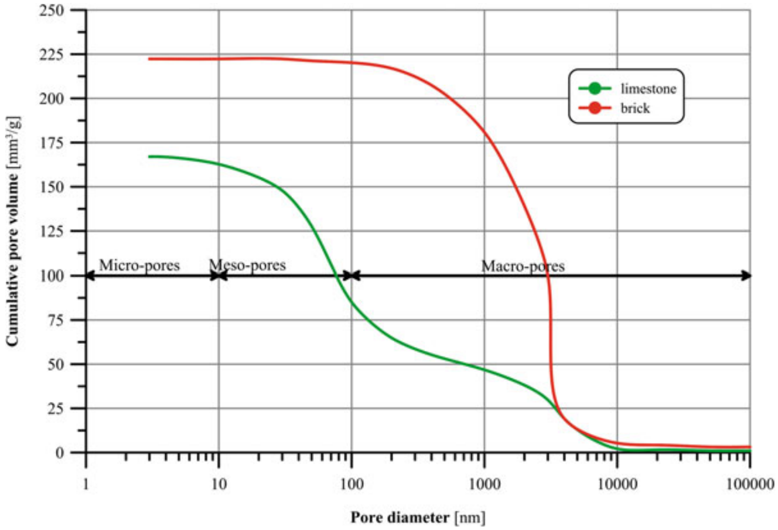


**Fig. 7.31** Pore size distribution of two typical building materials: brick (*red*) and limestone (*green*) (Taken from: Brocken 2012)

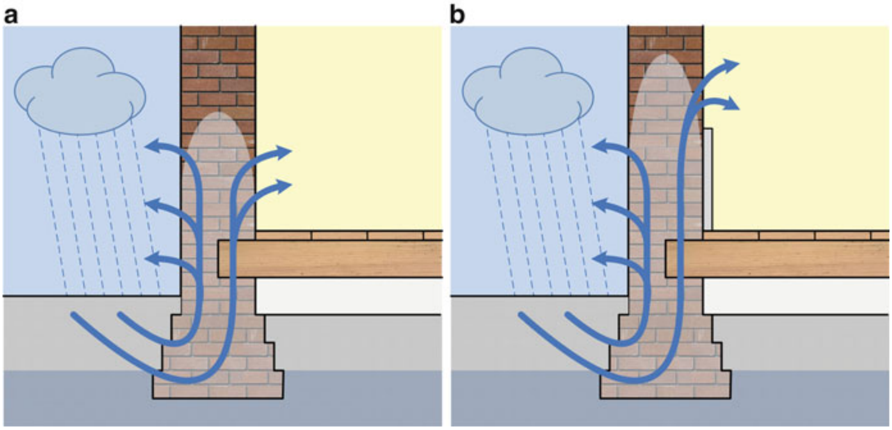


**Fig. 7.32** Rising damp in an outer wall without interior finishes (**a**) and rising damp in an outer wall with a vapor impermeable layer causing capillary water to rise higher (**b**)

sorption is rising damp. This phenomenon can manifest itself on the inside as well as the outside of buildings, see Fig. 7.32.

When a building or building material is wet or moist, and the environmental conditions are right, drying will occur in two stages. The first stage occurs when all the pores in a material are full of water. At the surface, water will evaporate. This will continue as long as there is liquid water present near the surface, for instance when a wall is connected to groundwater. This first drying stage is relatively fast. The second stage occurs when there is no more liquid water available at the surface, for instance when the evaporation rate is larger than the supply of liquid water from the inner core. In this case the evaporation front will be inside the material. At this front, liquid water will become water vapor. This water vapor then has to be transferred out of the material by diffusion, which is a relatively slow process. These differences in drying rates are the cause of building defects like frost damage and crypto efflorescence. Because of the slow drying process of the second stage, hygroscopic building materials like brick will stay wet for a long period of time after absorbing water during a rain shower. In cold climates where temperatures are below 0 °C (32 °F) absorbed rain water can freeze leading to frost damage. In building materials like brick it is very common that salts are present. When those salts are dissolved in water and drying occurs, whether to the outside or inside, salts will migrate. At the point where water evaporates salts will form crystals. Thus during the first stage the crystals will be formed on the surface (efflorescence) causing aesthetic loss but no actual damage to the brick. During the second stage crystals will be formed inside materials (crypto efflorescence). These crystals can cause crystallization pressures that might cause the face of the bricks to crumble and disintegrate.

## 7.5.4 Interstitial Condensation

Depending on the differences in the partial pressure of water vapor, water vapor will be transported from the outside to the inside or vice versa. In cold climates a specific risk can occur when warm moist air penetrates into the building structure. This process is facilitated when building materials, gypsum and brick with a low water vapor resistance factor are used. In cold climates, during periods with low outdoor temperatures, the buildings structure is cold on the outside but can be heated on the inside (Fig. 7.33). When insulation materials are used with a low wvrf

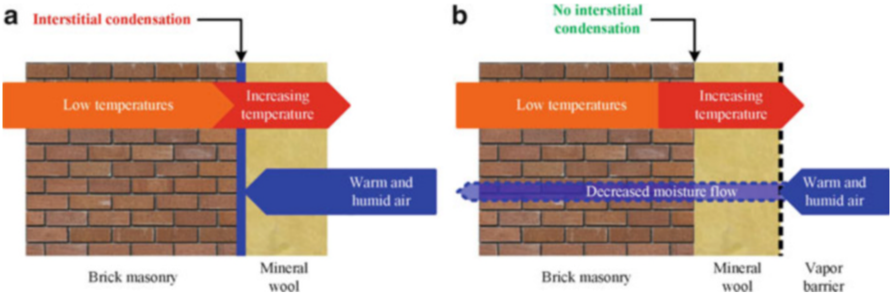


**Fig. 7.33** A schematic presentation of interstitial condensation (**a**) and how to prevent this (**b**)

the temperature difference can be quite large (see also Table 7.9) and moist air can penetrate into the building structure to the point where the structure's temperature is below the dew point and water vapor will condensate (Fig. 7.33a). At this point the partial vapor pressure exceeds the maximum vapor pressure. This is called interstitial condensation, and it occurs within the materials of the building structure. To prevent interstitial condensation, vapor barriers can be applied (Fig. 7.33b). These are located on the side with the highest temperature i.e. on the inside in cold regions and on the outside in hot and humid regions. This vapor barrier will prevent high vapor concentrations from penetrating into the structure thus decreasing the risk of interstitial condensation (Quirouette 1985).

The so-called equivalent air layer thickness (symbol: Sd, unit; m) is a measure to describe the effectiveness of any given material to prevent interstitial condensation. It can be calculated by multiplying the thickness (d) and water vapor resistance factor (wvrf) of a material. To prevent interstitial condensation the equivalent air layer thickness needs to be 0.5 m or more (Borsch-Laaks 2006). In Table 7.10 this value for various vapor barriers is provided.

The main purpose of an air barrier is to stop outside air from entering the building or vice versa through seams and cracks in the building fabric. The purpose of a vapor barrier is preventing diffusion through the building fabric. The latter is perfectly suited to prevent surface condensation inside the structure by stopping infiltration and exfiltration (Quirouette 1985). In practice both types of barriers are combined into one layer (foil). Care should be taken to ensure that seams of this foil are also air tight. Applying barriers in practice in such a way that air tightness in achieved, is very difficult. Extreme care should be taken when applying these foils and closing the seams (Fig. 7.34a, b).

Lime plasters or sprayed foam insulation will also reduce in- and exfiltration, but especially the foam insulation is obviously much less suitable in most historic buildings.

**Table 7.10** The equivalent air layer thickness of various vapor retarders and barriers

| Material | Thickness [mm] | Water vapor resistance factor (μ) [−] | Equivalent air layer thickness (Sd) [m] |
|---|---|---|---|
| Tar paper (single sided) | 0.15 | 580 | 0.087 |
| Tar paper (double sided) | 0.30 | 3,000 | 0.9 |
| Glass fleece | 2.0 | 4,000–60,000 | 8–120 |
| Polyvinylchloride foil | 0.1 | 9,000–45,000 | 0.9–4.5 |
| Polyethylene foil | 0.1 | 45,000–140,000 | 4.5–14 |
| Polyethylene foil | 0.3 | 34,000 | 10.2 |
| Polyester | 0.1 | 4,000 | 0.4 |
| Roofing felt (2×) and bitumen layers (3×) | 5.0 | 700,000 | 3,500 |
| Latex paint | 0.1 | 1,500 | 0.15 |
| Oil paint | 0.03 | 3,000–8,000 | 0.09–0.24 |

**Fig. 7.34** The application of vapor barriers is an import but sometimes difficult job: (**a**) a vapor barrier with very small overlap and weakly glued seems, this can become problematic in future and needs adjustment (Photo: Van der Wal, Cultural Heritage Agency of the Netherlands), (**b**) a properly executed vapor barrier with a sufficient overlap and properly glued seems as part of a wall closing protocol

### *7.5.5 Hygric Mass*

Fluctuations of the indoor relative humidity can sometimes be buffered by the hygroscopic mass of the building. For air exchange rates less than one per hour, hygroscopic walls and ceilings can stabilize the indoor relative humidity significantly (Padfield 1999). The larger the ability to absorb or desorb moisture from the surrounding air, the higher the hygric mass or storage capacity (specific hygroscopic moisture capacity: symbol: $\xi$, unit: kg/m$^3$). This capacity is easily readable from a hygroscopic curve. The steeper the curve, the higher the specific hygroscopic moisture capacity, see Fig. 7.35. In general all building materials have a higher moisture capacity at high relative humidity levels. But since most indoor climates in museums will have a relative humidity between 40 and 60 %, see the grey area in Fig. 7.35, gypsum plaster and wood are comparatively good buffers. From this figure it is also evident that (fired) brick, a common building material, has a rather poor storage capacity.

But even materials with high moisture capacity become useless as a hygric buffer when the rate at which they absorb or desorb is too fast or too slow. For materials the buffer efficiency depends not only on the specific hygroscopic moisture capacity but also on the resistance to water vapor transport, characterized by the water vapor permeability coefficient (symbol: $\delta$, unit: s). The rate at which vapor is absorbed or desorbed is given by the water vapor diffusivity (symbol: $D_v$, unit: m$^2$/s). The effective depth is a measure for the thickness of the wall that is actually used for buffering. The effective depth depends on the water vapor diffusivity and the length of a certain periodical fluctuation. The hygric buffer

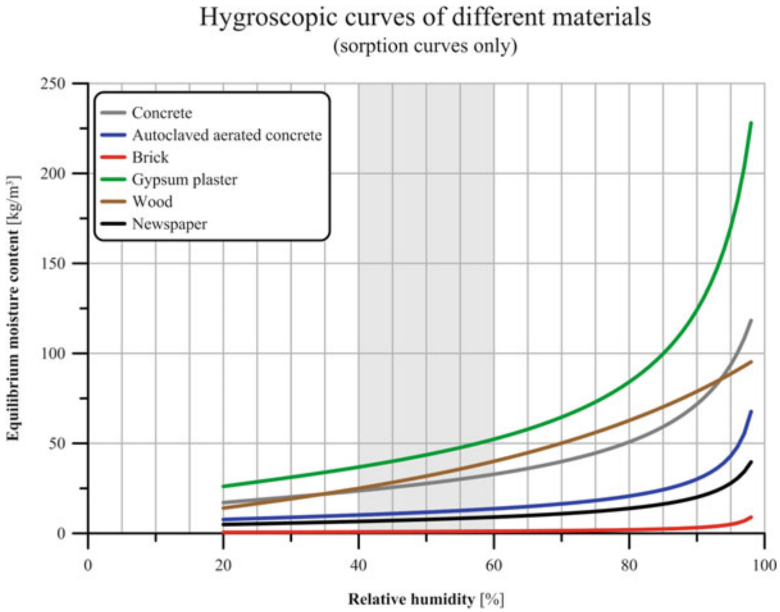


**Fig. 7.35** Hygroscopic sorption curves for different materials, the steepness of the curve is a good indicator for hygric storage: a steeper curve indicating better hygric storage (Based on data taken from: Hens 2003)

capacity is the product of the hygric mass and the effective depth. A material that is very thin will simply not have sufficient storage capacity, i.e. has a low hygric mass. A material that has a large hygric storage capacity but is a bad hygric conductor, i.e. a low vapor diffusivity, will absorb and desorb moisture too slowly for this property to be useful and vice versa. This relation is presented in Fig. 7.36. In general, the higher the water vapor permeability coefficient (or lower the water vapor resistance factor) the higher the effective depth and the better the overall hygric buffering performance. Note that the hygric buffer capacity is very similar to that of the thermal buffer capacity.

In Table 7.11 the effective depth is given for a diurnal cycle (24 h) for different building materials and for concrete also a 3 month (2,160 h) cycle. It shows that slow fluctuations will penetrate deeper into the building fabric. The effective depth of concrete changes from 0.3 to 2.4 cm comparing a diurnal and 3 month cycle. This is very small when compared to the effective depth for temperature. This means that the complete buffering of a diurnal or 3 months hygric cycle would require a thickness which is readily available in unfinished concrete walls. On the other hand, other materials require a thickness varying from 0.1 to 18.1 cm to buffer daily cycles. The materials with these thicknesses can be found in almost any building. The exception would be mineral wool, where the required depth of material is unlikely to be used. As can be seen from Table 7.11 concrete, lime plaster (best) and wood are good hygric buffers (high hygric buffer capacity). The

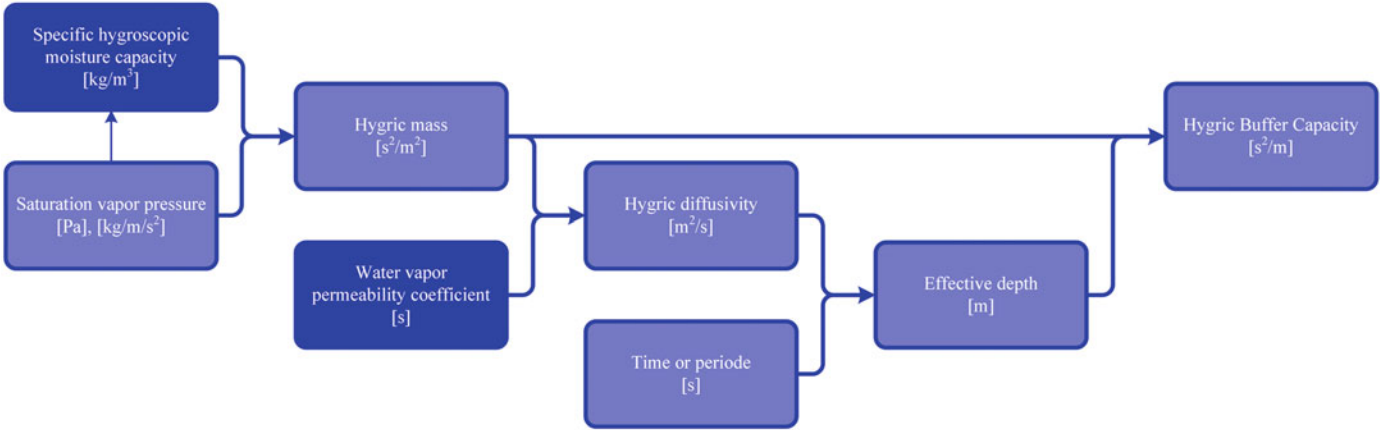


**Fig. 7.36** The relation between hygric properties (*solid boxes*), the hygric buffer capacity and the derived physical quantities of building materials

**Table 7.11** Effective depth calculated for different periods and building materials

| Material | Period<br>t [h] | Water vapor resistance factor<br>$\mu$ [−] | Specific hygroscopic moisture capacity<br>$\xi_{40-60}$ [kg/m$^3$] | Effective depth<br>d* [cm] | Hygric buffer capacity<br>$\times 10^6$ [s$^2$/m] |
|---|---|---|---|---|---|
| Concrete | 24 | 25 | 76.2 | 0.3 | 81.35 |
| | 2160 | 25 | 76.2 | 2.4 | 771.72 |
| Brick | 24 | 10 | 1.8 | 2.6 | 19.85 |
| Lime plaster | 24 | 6 | 74.9 | 0.5 | 164.71 |
| Wood | 24 | 100 | 73.1 | 0.1 | 39.85 |
| Mineral wool | 24 | 2 | 0.2 | 18.1 | 14.04 |

correspondence with the specific hygroscopic moisture capacity is large. Fired brick and mineral wool are unsuitable. Table 7.11 also shows that the thickness needed to buffer daily fluctuations in general is small (less than 0.5 cm). It should be noted that when the practical available depth is smaller than the theoretical effective depth, the hygric buffer capacity will be the product of the hygric mass and the available depth.

The best and most common buffering materials are wood, cut across the grain, and unfired clay brick (Padfield 1999). Not all of those materials are traditional building materials and some of them have other disadvantages. Note that good thermal buffer materials are not necessarily good hygric buffer materials and vice versa.

## 7.6 Conclusion

In the past decades the tendency in the heritage field was to gain control over the indoor climate primarily by mechanical equipment. Buildings were adapted to this new hygrothermal balance by making them more airtight and sometimes by applying water vapor barriers. More and more the characteristics of the materials used are chosen based on their ability to positively influence the indoor climate and thereby reduce the capacity of mechanical systems. To make the right choices it is important to know what the current indoor climate is, and how this is influenced by the building fabric and construction. The next seven steps might serve as a guide to start understanding the indoor climate:

1. Determine the orientation of the building and solar gains, wind speeds and wind directions for the building location. These parameters can be measured independently or obtained from a local weather station;
2. Inspect the building on the outside and inside for possible defects. Several visually observable phenomena can help identify problems in the building

envelope: salt efflorescence, algae growth, wet areas, cracks, seams, surface or interstitial condensation, mold growth etc.;

3. Take measurements of the outdoor and indoor climate. The temperature and relative humidity over a period of time give insight in the possible climate risks for the building, interior or collection as presented in Chaps. 4 and 5. Comparison with the outdoor climate gives insight in to how the building affects the indoor climate. The outdoor climate can be measured independently or obtained from a local weather station. The indoor climate also can be measured independently as described in Appendix 4, Fig. A4.1 or can be outsourced to a commercial company;
4. Make an assessment of the hygrothermal properties of the building envelope as described in Sects. 7.3, 7.4, and 7.5 to understand why there is a difference between the outdoor and indoor climate. Gather information on the building envelope regarding: the type of building materials, dimensions of transparent and non-transparent surfaces, layers of building construction from outside to inside, connections between different building parts, etc.;
5. Make an assessment of the air exchange rate;
6. Make an assessment of internal heat and moisture sources and sinks, considering both dynamic and static sources and sinks. Estimate how each zone is influenced by these sources, or sinks, for how long and at which interval. Typical static sources are electrical equipment, plants, etc. Typical dynamic sources are climate systems, people, etc.;
7. Make an analysis of the gathered data. Keep in mind when looking at climate data whether or not these form an actual threat to the building, interior, or collection. Establish whether any indoor climate parameter is a threat: temperature, relative humidity, or their fluctuations. Be precise. Then try to understand why this parameter differs from the optimal. Use the first barrier principle as described in Sect. 7.2 to find the aspects of the building that play a role in how the indoor climate is formed.

The results of this step can be manifold, varying from climatic data presented in figures to a full analysis of the building physics in a comprehensive report. Once the indoor climate is understood in more detail, any optimization of the indoor climate can start with improving the building physics. Depending on the decision to be made a choice should be made on which of the above steps will provide enough information to make an well informed decision. It can be very helpful to use a floor plan in which the climate zones are presented to indicate e.g. moisture and temperature sources and sinks.

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# Chapter 8
# Step 7: Defining Climate Specifications

**Abstract** The starting point when optimizing any indoor climate is knowing what the current indoor climate actually is, understanding how this indoor climate is formed, and if the collection or the building are at risk, and/or if the visitors and staff are (un)comfortable. When it is decided to optimize the indoor climate the first step is to identify what is important to you for the decision at hand.

In this chapter the process of combining collection, building and human needs is described. An optimal climate for collections can be detrimental to the building and/or very uncomfortable to people and vice versa. Examples of new risks resulting from a specific climate control objective are provided.

The process starts by projecting the desired functionality for each room, the climate zones and the current climate in each zone onto a map of the building. Secondly, the collection is divided into collection units, ideally based on objects with similar susceptibility. For each collection unit the relevance of controlling a specific climate parameter is indicated. Then, the values between which the relative humidity and temperature set point and the acceptable relative humidity and temperature fluctuations can be chosen. Examples of an approach for balancing these requirements is given to help explain how this process works in practice.

**Keywords** Combining collection, building and human needs • Balancing climate specifications • Zoning • Climate specification process

## 8.1 Introduction

Traditionally climate specifications were provided as a set of six numbers, indicating the set points and acceptable hourly and/or seasonally fluctuations for temperature and relative humidity and the rate of change of the fluctuation in time. These numbers could be found in (inter)national standards, (inter)national loan requirements and easily be copied into the list of requirements made by museum professionals, architects, consultants and engineers. A thorough analysis of the collection's (cultural) values and/or susceptibility was not required. Specifications were based on the best technically achievable climate, on the implementation of climate control systems, and adaptation of the building to the new indoor climate.

B. Ankersmit, M.H.L. Stappers, *Managing Indoor Climate Risks in Museums*,
Cultural Heritage Science, DOI 10.1007/978-3-319-34241-2_8

Questions were focused on adjusting the building physics, floor loading issues and hiding possible ducts and pipes from direct sight.

In this publication we work towards affordable, tailor-made, indoor climate conditions for collections and the building. The starting point when optimizing the indoor climate is knowing what the current indoor climate actually is and understand how this indoor climate is formed (Chap. 7: Step 6), and if the collection is at risk (Chap. 4: Step 3); or the building is at risk (Chap. 5: Step 4), or if the visitors and staff are (un)comfortable (Chap. 6: Step 5). The original objectives of the decision (Chap. 2: Step 1) form the foundation for the decision to be made. Within this decision making the cultural values of the building and the collection (Chap. 3: Step 2) form an essential basis. These (cultural) values of the building can be weighed against those of the collection, see Fig. 3.3, which allows a rough analysis of the possibilities for climate control. When the collection is (much) more valuable than the building, the indoor climate can be designed as a preservation environment with an emphasis on relative humidity and/or temperature control. Changes to the building to improve the building physics, or implementation of a climate control strategy, will most likely involve a loss of cultural value. If the building is much more valuable than the collection, then the climate will be aimed at preserving the building values and accepting (some) climate risks to the moveable collection.

Bringing all the arguments into the decision making process and weighing these findings against other ambitions, requirements and boundary conditions is a complex process. In real life the climate specifications depend not only on the cultural values, the susceptibility of the building and the collection, and the comfort requirements, but also on other arguments such as financial and technical feasibility, and the desire to have incoming loans, which often play an important role in defining climate specifications.

Decisions to optimize the indoor climate are regularly based on an individual's intuition: "*I think the climate is fluctuating too much ……. and …… this is not good for the collection……*", a statement that is not very precise and does not really help in guiding a decision. Understanding the indoor climate requires measuring it. The results of these measurements can then be used for an analysis of the climate risks to the collection, the building, or people's discomfort. When climate data is collected digitally, the results can easily be inserted into the risk models for mold, chemical deterioration and mechanical damage (see Fig. 8.5).

Specifying the indoor climate numerically is not easy, but quite necessary. The numbers are essential to design an air-conditioning system and the necessary adaptations to the building's construction. In a museum context, contrary to almost all other indoor environments in public buildings, it is important to control the relative humidity to avoid high or low extremes and too large fluctuations. So (de) humidification capacities need to be calculated. These calculations can also be used to assess the expected energy consumption. After changing the building and/or implementation of a climate control system, the numbers can be used as a reference for climate measurements to analyze the systems' performance.

**Fig. 8.1** Low temperatures in this unheated palace in Koeskovo, Moscow during winter time makes the indoor climate uncomfortable to staff and visitors but will help preserving the interiors

## 8.2 Combining Collection, Building and Human Needs

It is clear that an optimal climate for collections can be uncomfortable to people (see Fig. 8.1) and/or detrimental to the building (see Fig. 8.2). On the other hand climate specifications solely based on human comfort will not always be optimal for the collection's preservation. Some of these negative effects resulting from options to develop single objectives are presented in Table 8.1.

## 8.3 Zoning

When the building is redeveloped or the museum refurbished the indoor climate often becomes important. To put the theory about the need for a specific indoor climate into practice, it is helpful to see the building's layout as a set of different climate zones. Quite similar to the zoning that many museums have developed to control fire risks or to manage security.

**Fig. 8.2** Adding moisture to the indoor climate in winter can result in water running down the glazing and the uninsulated wall

In practice, it is rare that all three climate requirements are equally important for all climate zones in a museum. In Table 8.2 the typical climate zones found in museums are given. Some climate zones, like storage rooms and exhibition spaces are specifically meant to house collections. Offices, are generally designed for human comfort and not for collection preservation. Obviously, in those zones where both staff and visitors are brought together with collections, the indoor climate will most likely be a compromise of an optimum climate for the collection and users.

The zones that are specifically used by people, such as offices, the restaurant etc. require a comfortable climate for people. This means that temperature control is more important than control of the relative humidity. In cold climates this generally means heating of the indoor air, while in warm regions cooling and/or ventilation is required. The relative humidity in these rooms is uncontrolled, free floating and will have large short and long term fluctuations. In collection zones in which human comfort is less important, the control of relative humidity is more relevant. Dry outdoor air will be humidified and humid outdoor air will be dehumidified to maintain a specific indoor relative humidity.

Examples of these special environments are the low temperature storage rooms for highly sensitive materials and conservation heating of storage rooms in humid

**Table 8.1** The new climate risks that might result from a specific climate control objective

| | Objectives | | |
|---|---|---|---|
| Risks to | Collection needs | Building needs | Human needs |
| Collection | | Relative humidity fluctuations increase the risk of mechanical damage to susceptible collections | Heating to increase human comfort in cold climates, increasing the risk of mold and rot |
| | | Allowing low relative humidity in winter will increase the risk of mechanical damage to susceptible collections | Cooling might increase the risk of locally high relative humidity with an increase of biological decay and relative humidity gradients in time and space with an increase of mechanical risks |
| | | | High ventilation might cause temperature and relative humidity fluctuations, increasing the mechanical risk to susceptible collections |
| Building | Control of the moisture balance might cause high relative humidity conditions in cold locations in the building envelope, increasing the risk of mold and rot | | Intermittent heating or cooling for human comfort will increase the risk of mechanical damage to susceptible finishes and salt efflorescence due to relative humidity fluctuations |
| | A continuous lower relative humidity indoors will increase the risk of salt efflorescence, where present | | |
| Human | Low temperatures to reduce the risk of chemical deterioration will make the indoor climate uncomfortable to staff and visitors | High ventilation rates can be uncomfortable to staff and visitors due to draughts | |
| | Stabilizing the relative humidity by temperature control (i.e. conservation heating) might result in high temperatures and thus discomfort, during warm seasons | | |

**Table 8.2** Typical climate zones found in a museum (These are often similar to the safety zones)

| Collection zone | Mixed zone | People zone |
|---|---|---|
| Permanent store rooms, typical microclimates such as showcases, cabinets etc. | (Permanent store room), transit store room, exhibition galleries, study rooms, conservation laboratories, photo studio, collection packing area | Foyer, lobby, restaurant, shop, lecture rooms, offices, server room, loading bay |

regions (Maekawa and Toledo 2003). Obviously, the requirements for human comfort were insignificant in the decision making for those repositories. It should be noted however that, defining the temperature at which the storage should be kept is a fine tuning process. The objective is to find the optimum temperature balancing the discomfort of staff, researchers and potential visitors. At low temperatures the fine motor skills that are required to handle delicate objects will be reduced, while at elevated temperatures people become physically uncomfortable. To assess the relevance of the need for human comfort it is important to analyze how often staff enter the cold or hot store room(s) and for how much time. Temporary heating/cooling of the store room can be considered to overcome the discomfort at specific moments when staff will have to work inside the storage room for prolonged times, e.g. to prepare an exhibition.

The biggest challenge is to define the climate specifications of the mixed zones were collection needs are just as important as human comfort. Especially in extreme climates.

In cold climates where the indoor temperature is maintained at comfort levels, the relative humidity will be low and additional humidification is often required for collection preservation. Changing the moisture balance requires careful examination of the building physics. Traditionally the building was fully adapted to this new indoor climate by changing the insulation, infiltration and moisture barrier properties. That these changes resulted in a loss of cultural values to the building seemed to be much less important than the possible deterioration of the movable collection. In cases where the cultural value of the collection is much higher than the cultural value of the building these adaptions can be made without much loss of architectural or historic value. But in cases where the building is of equal value to the collection, finding an optimum for the preservation of cultural values becomes much more difficult.

In hot and humid climates human comfort was traditionally provided by shading and ventilation. This will result in fluctuations of temperature and relative humidity. Reducing infiltration combined with additional cooling will reduce the temperature and often to a certain extent also the relative humidity. But removal of condensate from the cooling unit might require a drain to go through an historic important wall or floor.

## 8.4 The Process

The process to derive the numerical specifications that describe the future indoor climate, is complicated. It is complicated because the knowledge of different scientific areas needs to be combined without only thinking about solutions to solve the problem. In many discussions about optimizing the indoor climate, the debate narrows down to which option is best. It is important to keep an open mind and to hear all stakeholders involved. Ideally a group of stakeholders comes together to discuss the issues that are involved in finding the optimal climate specifications, based on the balance between preserving cultural values of both building and collection and creating a welcoming atmosphere for visitors and museum staff. Having this discussion in the building that needs to be refurbished, renovated or redesigned will help in having a shared idea of the challenges and possible options. In an open discussion the collection manager(s), the climate engineer, the (conservation) scientist, the building physicist, the contractor, the architect and the climate consultant will have to discuss goals and boundary conditions. In the discussion several themes have to be brought together: cultural values, the collection needs, building needs, human comfort and building physics. Every stakeholder explains what is important to him/her and why, and identifies the boundaries in which the options can be developed (Table 8.3).

Given the level of interests and specific goals of each of the stakeholders the discussion to reach the optimum climate specifications is complex. The conservator and (conservation) scientist will be key in identifying a possible incorrect indoor climate. The curator, director and (restoration) architect will have a view on how the building will be used and designed. The building engineering physicist and the climate consultant engineer will have ideas on control strategies. In the process it is paramount that each of the stakeholders can bring in their expertise. It is advisable to have an independent moderator who can encourage everyone to take part in the discussion and keep focus at the decision to be made. In Fig. 8.3 the complexity of the decision making with this group of stakeholders is depicted schematically. To maintain this focus the discussion leader might ask participants questions that stimulate evaluation, such as:

- Are we focusing on the right issue?
- Do we really understand each other or do we need to backtrack to make sure we are really grounded in what is important?
- What else do we need to consider or investigate to specify the desired indoor climate?

Obviously when thinking about specifications, the options to solve climatic issues will be brought into the discussion too. By talking about options, most likely new risks become relevant which will drive the discussion about the climate specifications. Similarly, when talking about design and use, new options will be developed that in turn will influence the design and/or use of the building or zones. The discussion is not linear and will iterate around these subjects several times before it is clear to all involved what the decision context is.

**Table 8.3** The stakeholders with their typical interests and goals

| | Function | Typical interests | Goals |
|---|---|---|---|
| Museum | (General) director | Collection/people/budget | Providing a comfortable visit |
| | | | Stay within the budget |
| | | | Building should look nice |
| | Conservator | Object/material/construction | Object(s) preservation |
| | Curator | Collection unit/object | Object(s) preservation |
| | | | Object(s) should be used to tell stories |
| | Facility manager | Building | Building preservation |
| | | | Visitor comfort |
| | | | Manageable (climate control) systems |
| External | Building engineer | Building/zone | Building should be developed to allow a specific environment |
| | Climate system engineer | Building | Climate control system(s) should be reliable and provide the climate required |
| | Conservation scientist | Object/building | Finding a balance between object and building preservation |
| | | | Providing scientific knowledge and possibly case studies |
| | (Restoration) Architect | Building/people | Translating the goals from all stakeholders to a realistic plan |
| Local authorities | Building services | Building | Reviewing the plan (legislation) |
| | Environmental services | City | Reviewing the plan for environmental impact (legislation) |
| | (Cultural) heritage | Building/collection | Reviewing the plan for impact on cultural value (legislation) |
| National authorities | Building services | Building | Reviewing the plan (legislation/costs/people) |
| | Cultural heritage | Building/collection | Reviewing the plan (legislation/cultural value) |

To help going through this process it might be practical to critically evaluate floor plans in which the new environmental conditions are projected. On this floor plan the following can be indicated:

- The desired functionality for each room (see Table 8.2).
- The desired climate zones. This can be done by drawing a thick colored line over the floor plan for every zone that is to be separated from the other.
- The current climate in each zone. When measured data is not available the indoor climate can be estimated based on data known for similar spaces or by modeling the outdoor climate coming in.
- The desired indoor climate based on human comfort needs

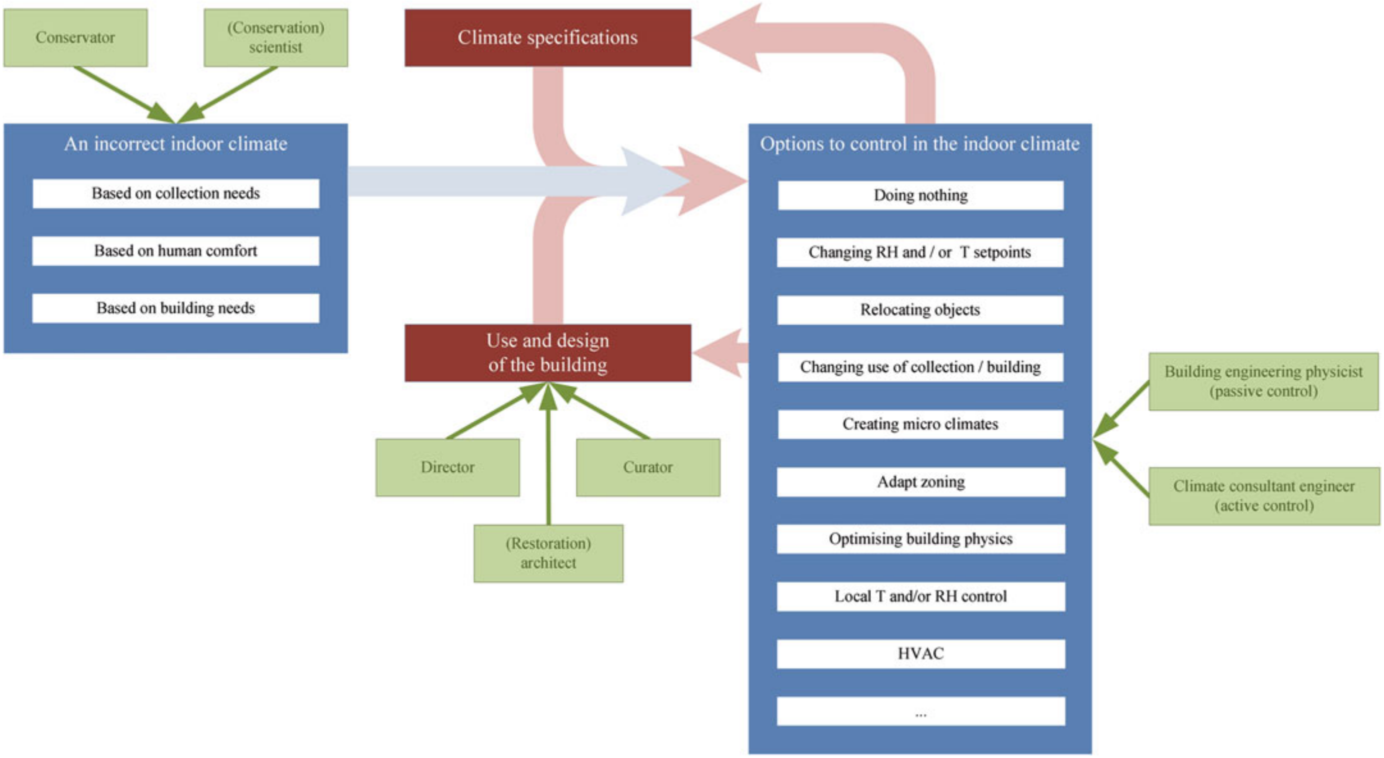

**Fig. 8.3** The schematic representation of the discussion and it’s stakeholders

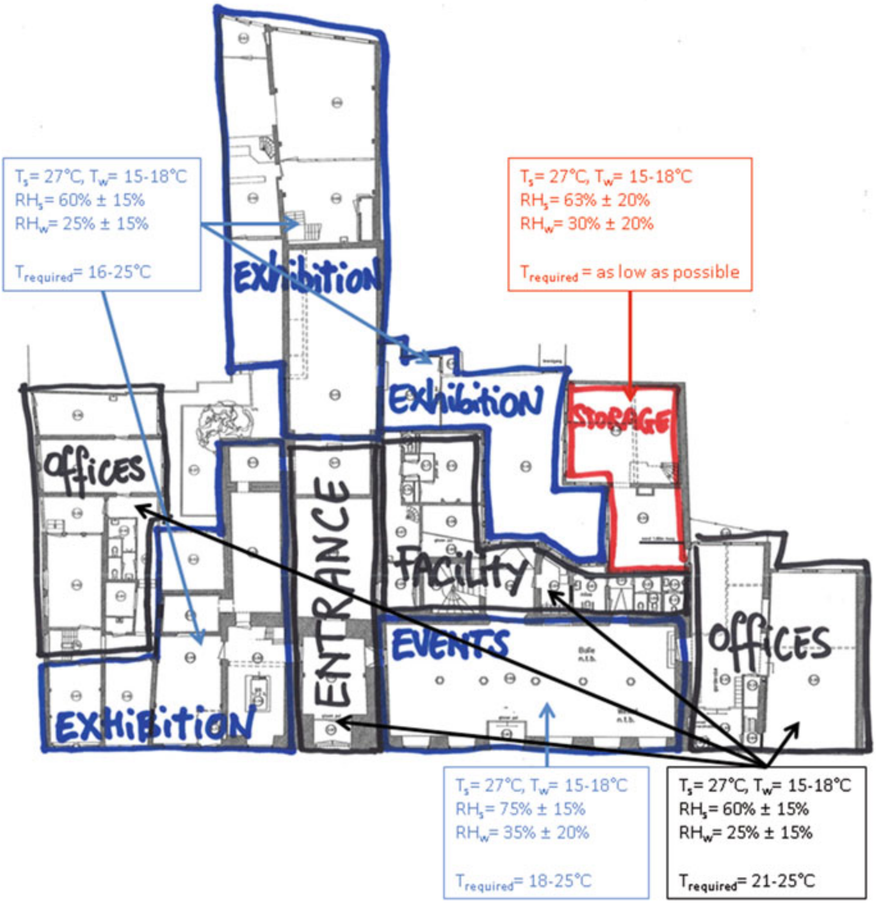

**Fig. 8.4** Example of a floor plan indicating different climate zones and the current climate in summer (s) and winter (w) in each zone climate including the desired human comfort specifications

In Fig. 8.4 an imaginary example is provided indicating different climate zones projected on a floor plan of an historic building. The summer climate in the building can reach temperatures of around 27 °C (81 °F), while in winter the temperature indoors depends on the set point of the thermostat. The relative humidity varies greatly indoors due to orientation, isolation and the use of natural ventilation. For the new functions inside the building, exhibition spaces, offices, storage room and event room, the temperature specifications are presented as $T_{required}$. The next step is to define the relative humidity specifications for the zones.

As an example, an imaginary exhibition in one climate zone will be discussed in more detail. Again the process starts with the current climate in the zone. This is ideally known by measurements, but can also be deduced from data in similar buildings or zones with equal physical building qualities. Based on climate data from similar locations, the climate in this zone is expected to be:

| | Summer | Winter |
|---|---|---|
| Temperature | 22–28 °C (72–82 °F) | 18–20 °C (64–68 °F) |
| Relative humidity | 55–75 % | 35–50 % |

For human comfort the desired climate was formulated as:

| | Summer | Winter |
|---|---|---|
| Temperature | 22–25 °C (72–77 °F) | 18–21 °C (64–70 °F) |
| Relative humidity | 20–80 % | 20–80 % |

The imaginary collection that will be present in this zone is: 10 paintings on canvas, 5 wooden statues, 15 works on paper, 2 textiles and 2 bronze statues. The collection is divided into collection units. These units can be based on different aspects. Using type of object, often includes materials and construction results on collection units with similar susceptibility. For each collection unit the relevance of controlling a specific climate parameter can be indicated. In Table 8.4 an example is provided using color codes, in which green indicates not important to control, orange means possibly important to control, while red means important to control.

Based on the specific construction and condition of the most valuable objects in the collection units the desired climate conditions can be given, see Chap. 4, step 3 for more background information. For each collection unit the next step is to numerically define:

- Between which values can the relative humidity set point be chosen?
- Between which values can the temperature set point be chosen?

**Table 8.4** The relative importance of controlling a specific climate parameter of the indoor climate for different types of collections

| | **Temperature**[*] | | **Relative Humidity**[*] | |
|---|---|---|---|---|
| | **Set point** | **Fluctuations** | **Set point** | **Fluctuations** |
| **10 Paintings on canvas** | Small risk of chemical degradation | 🟩 | Small risk of chemical degradation | Risk of mechanical degradation |
| **5 Wooden statues** | Small risk of chemical degradation | 🟩 | Small risk of chemical degradation | Risk of mechanical degradation |
| **15 Works on paper** | Risk of chemical degradation | 🟩 | Risk of chemical degradation | Small risk of mechanical degradation |
| **2 Textiles** | Small risk of chemical degradation | 🟩 | Small risk of chemical degradation | Small risk of mechanical degradation |
| **2 Bronze sculptures** | 🟩 | 🟩 | Small risk of chemical degradation | 🟩 |

*Green*: relatively unimportant to control, *orange*: might be relatively important to control, *red*: is relatively important to control

**Table 8.5** The climate specifications for different collection units in an imaginary collection as was specified by an imaginary staff

| | Temperature (°C) | | Relative humidity (%) | |
|---|---|---|---|---|
| | Set point | Acceptable fluctuations | Set point | Acceptable Fluctuations |
| Paintings on canvas | 13–25<br>(55–77 °F) | n.a. | 40–55 | 5–10 |
| Wooden statues | 13–25<br>(55–77 °F) | n.a. | 40–55 | 5–10 |
| Works on paper | Cool | n.a. | 45–55 | 10–20 |
| Textiles | Cool | n.a. | 40–55 | 10–20 |
| Bronze sculptures | n.a. | n.a. | 30–60 | n.a. |

- What are the acceptable relative humidity fluctuations?
- What are the acceptable temperature fluctuations?

In Table 8.5 the climate specifications of this imaginary collection are provided.

The discussion will finally focus on the current climate data that falls outside the desired climate parameters. In this case the temperature in summer can be slightly higher than desired for the collection. So the question will be if some form of cooling is needed, and how is this done within the boundaries of cultural values and finances. Developing options to cool involves thinking about how these options might change the design, the cultural values of the building, or the experience of the visitors. Similarly, if the relative humidity set point should be between 40 and 55 % and fluctuations should be minimized to 5 %, than some humidification is required to prevent the low relative humidity in winter and some dehumidification in summer to reduce the peaks.

Several options should be considered. The first question to be answered is ‘how many objects determined the indoor climate specifications?’ if this a limited amount than relocation of these objects to a naturally more stable zone can be considered. Often this zone can be found deeper inside the building, because the outside climate generally has less influence on these spaces. Secondly, protection by microclimates might further reduce the need for climate control on a zone level. Changes to the building to reduce the impact of the outdoor climate can also be looked at. In this process it is important to continuously iterate between cultural values and options to optimize the indoor climate. Questions such as, ‘what will the climate be if this option is implemented and how will it change the use of the collection, the values of my building, the risks to the building? will help in analyzing the effect of different options.

In this case the three most susceptible paintings can be presented in microclimate boxes, while the others have no risk of mechanical damage due to relative humidity fluctuations of 10 %. The wooden statue that required a maximum 5 % relative humidity fluctuations is presented inside a showcase. The risk of chemical deterioration due to temperature was accepted because the loss of cultural values to the building and the financial implications were unacceptable when cooling of the air is implemented.

So the final climate specification was determined to be:

| | Temperature (°C) | | Relative humidity (%) | |
|---|---|---|---|---|
| | Set point | Acceptable fluctuations | Set point | Acceptable fluctuations |
| Summer | 23.5 (74.5 °F) | 1.5 | 55 | 10 |
| Winter | 20 (66 °F) | 2 | 45 | 10 |

## 8.5 A Case Study

Defining the desired indoor climate can take place in two ways. Analysis of the current climate risks can be done by using knowledge about the risks of the past, or by analyzing the material properties of objects. The latter was presented before. In this section the relative humidity specifications are developed based on the historic climate. To define the acceptable relative humidity fluctuations the so-called proofed fluctuation is determined. “The proofed relative humidity or temperature is the largest relative humidity or temperature fluctuation to which the object has been exposed in the past or, alternatively, just the lowest and highest relative humidity and temperature of the past. The risk of further mechanical damage (beyond that already accumulated) from fluctuations smaller than the proofed value is extremely low.” (Michalski 2007).

This analysis requires access to climate data over a prolonged time for the location. The grand salon in the Amerongen Castle provides the case study (see Fig. 8.5). In Sect. 10.5 Amerongen Castle is also described.

The grand salon is the most beautifully decorated room of the castle. Here important guests were received, it provides a beautiful view over the floodplains. The room is decorated with a large number of royal portraits, including those of William the Silent, Louise de Coligny, Maurice, Frederick Henry and the King William III. The marble mantelpieces dating from 1684 were made in Dresden. Several beautifully decorated pieces of furniture, among which two cabinets (see Fig. 8.6) were made around 1700 by the Amsterdam cabinetmaker Jan van Meekeren.

Often, the amount of climate data in these kind of locations is limited. Due to the highly valued interiors of the castle, climate measurements were recorded for prolonged periods of time, see Fig. 8.7. Since neither the heating nor the moisture balance were changed in the past decades it is believed that 1 year’s data could be used as an indicator for the previous years. Despite the fact that the outdoor climate during this time will have varied to a certain extent.

Analysis of the data indicates that the current indoor climate in the salon could be optimized. A relative humidity distribution of 35–80 %, with an average of

**Fig. 8.5** The grand salon of Castle Amerongen with many objects of great national value

**Fig. 8.6** The cabinet of Van Meekeren in the grand salon of Castle Amerongen

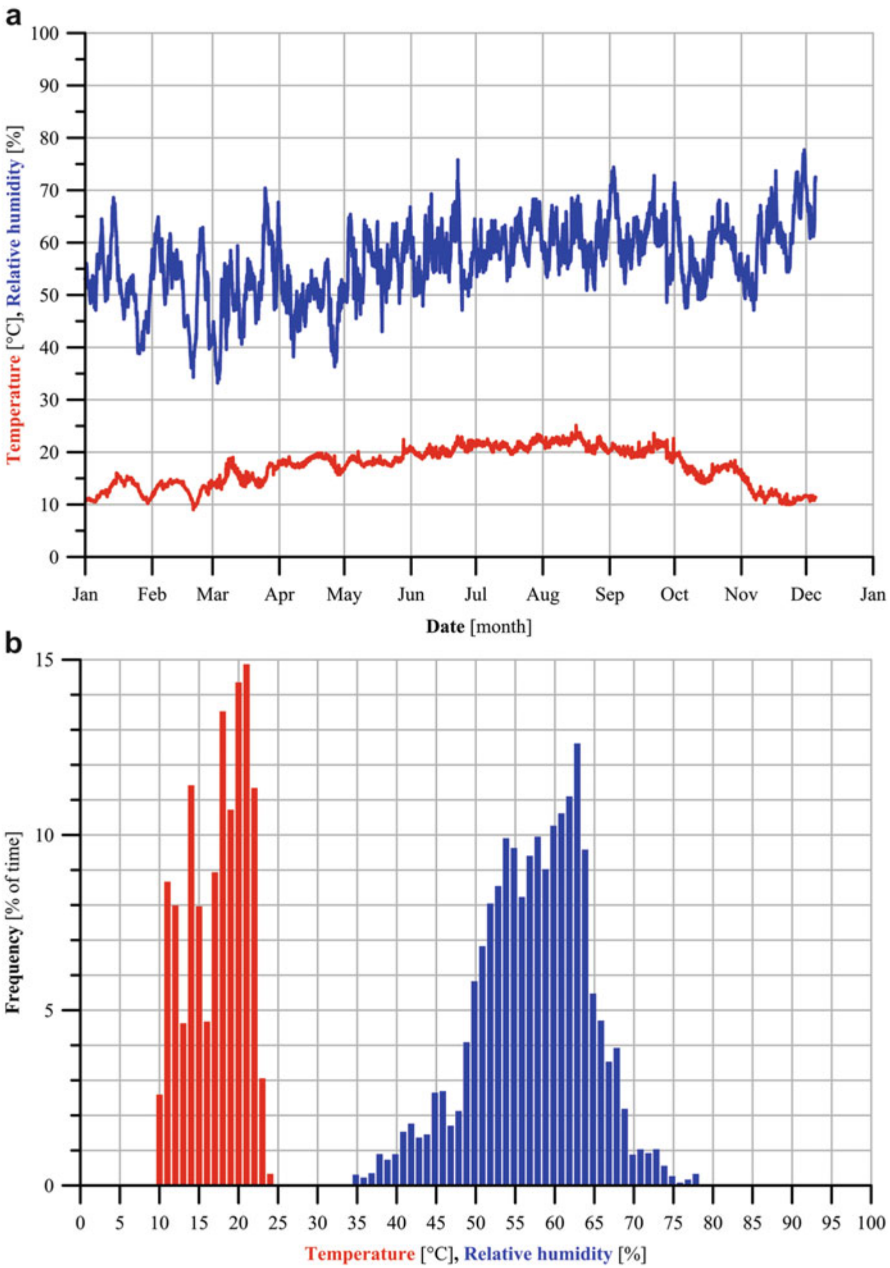

**Fig. 8.7** (**a**) Temperature and relative humidity plots for the climate in the salon of Castle Amerongen in 2011. (**b**) the distribution of temperature (*in red*) and relative humidity (*in blue*)

56.4 % and a standard deviation of 7.2 % were calculated. Since climate specifications generally take an overshoot and undershoot of about 8 % of the time into account, to cover for excess climate conditions, relative humidity climate specifications based on this analysis would be: 56 ± 7 % without a significant risk of mechanical damage due to relative humidity fluctuations. Similarly the temperature can be specified as 17 ± 4 °C (63 ± 7 °F). So simply: annual average ± one standard deviation.

Ideally the temperature should be as low as possible to reduce every chemical reaction that takes place within the collection. The Amerongen salon is already quite cold during winter time (~12 °C/54 °F) see the red line in Fig. 8.7a. Chemically unstable materials will degrade significantly faster when temperatures are high during summer times, as can be seen in Fig. 8.8a.

Obviously human comfort in the salon of Castle Amerongen is low. When the climate data for this room is plotted in the Adaptive Thermal Guideline (van der Linden 2006), see Fig. 8.8b, it is clear that it is too cold most of the time. Even though temperatures are too low for optimal visitor comfort, the museum decided that collection needs overrule human needs and the house will not be heated in winter. Similar to most estates managed by the National Trust in England that are either closed in winter or have restricted access (Lloyd 2006).

## 8.6 Conclusions

Bringing all arguments together and deciding what the indoor climate in a room or of a zone in a museum should be is not easy. The priorities of the institution, values of the building and collection, as well as their needs and those of users, will shape the final specifications and requirements of any climate optimization. Combining technical information about building physics, material science and human behavior with design and cultural experiences requires a process in which very different stakeholders are to be heard. An independent moderator can lead the group of stakeholders through a process in which different types of information is shared, discussed and evaluated, leading finally to a set of 8 numbers that can be used to develop the optimum mitigation strategy.

The result of this step is a table in which for each zone the climate set points and the acceptable fluctuations for relative humidity and temperature are specified for each season.

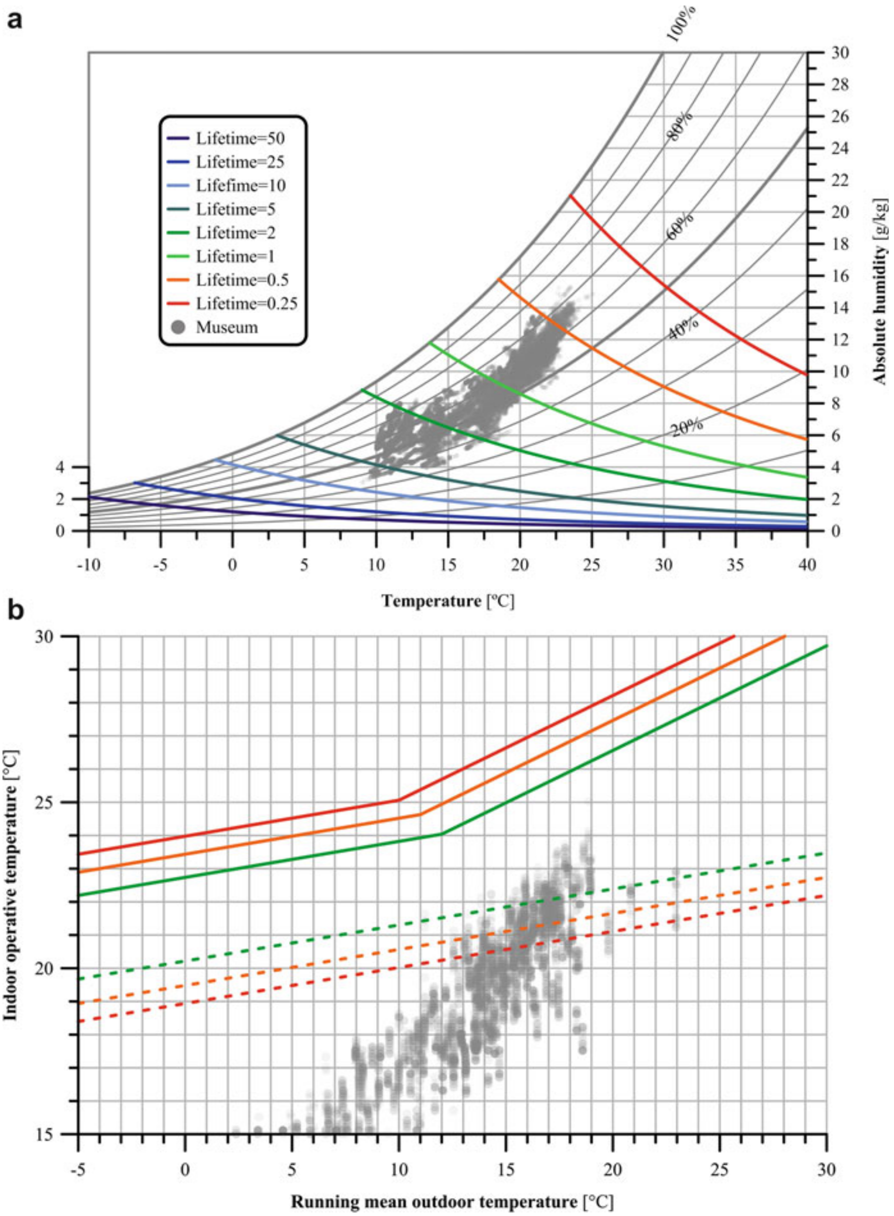

**Fig. 8.8** (**a**) The indoor climate for 2011 in the salon of Castle Amerongen plotted in a psychrometric chart showing the *lines* of equal relative lifetimes and (**b**) a thermal comfort assessment of the salon climate during opening hours (09:00–18:00 in 2011)

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# Chapter 9
# Step 8: Mitigating Strategies

**Abstract** Mitigating climate risks to collections and the building, or optimizing human comfort, includes improving physical properties of the building and often implementing a climate control system that fits the specific situation. In this chapter the improvements that can be made to the building envelope, to reduce the impact of the outdoor climate on the indoor climate, are discussed. This ultimately leads to the search for low energy climatised storage facilities. In which passive geothermal temperature control is combined with solar energy to allow dehumidification. Climate control at the object level is best realized by microclimates.

Actively changing the hygrothermal properties of the indoor air is done by air conditioning systems with the basic functions of heating, cooling, humidification, dehumidification, ventilation, and air purification (filtering). In smaller heritage institutes only specific functionalities are used by mobile devices, such as humidifiers or air conditioners to cool.

Large heritage institutes with large visitor numbers often choose to control the indoor climate using full climate control. This allows increasing precision in controlling the relative humidity and temperature and control over air ventilation, filtering, and air distribution of the entire space. The quality of control depends on the layout of the zones within the building and the HVAC systems. The long term performance of the systems depends on management and maintenance.

**Keywords** Mitigating climate risks • Climate control • Control strategies • Architectural measures • Sustainability • Control concepts

## 9.1 Introduction

Now that the value assessment has provided the fundamentals (Chap. 2: Step 1), the risks to the collection and/or the building are identified and/or the discomfort to users have been analyzed (Chaps. 3, 4, and 5: Steps 2, 3 and 4) and the physical possibilities of the building have provided the boundary conditions (Chap. 7: Step 6), a climate control strategy can be developed based on the objectives that were established (Chap. 6: Step 5).

Any potential climatic optimization should be critically reviewed to determine the way it changes the (cultural) values of the building; the way it changes the risks

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Cultural Heritage Science, DOI 10.1007/978-3-319-34241-2_9

to the collection and/or building; the way it changes the moisture and heat balance of the building; and the way the objectives are realized. Obviously, it must be verified that the desired climate conditions fit the permissible environment for the building. Generally three basic climate optimization strategies can be distinguished:

- The collection can be separated from the overall indoor climate by means of barriers resulting in local micro climates.
- The building physics can be adjusted.
- The indoor climate can be adjusted at the room/building level using mechanical climate control systems.

Often, in practice a combination of these is used. Defining the indoor climate, finding the optimal balance between building physics and (mechanical) climate control systems and maintaining as much (cultural) value as possible, requires the input of a team of experts from different fields. Depending on the size of the project, curators, building physicists, engineers, conservators, architects, scientists and HVAC engineers need to discuss the outcomes of the results of going through steps 1–6 and jointly need to sketch a rough outline of the climate control strategy. The larger the project, the more money is involved and often more (cultural) value is at stake, the more time is needed to go through the steps. More importantly larger projects require a process in which these steps are revisited a number of times to develop an optimal solution for a complex situation. This cyclic procedure is schematically illustrated in Fig. 1.4.

The primary stakeholders weigh the options for climate control and ultimately make a choice. An integral schedule of requirements (iSoR) is then prepared in consultation with (external) advisors. The iSoR generally contains, the vision and ambition of the project, challenges and opportunities, principles, functional requirements and logistics, security measures, construction and architectural requirements, technical requirements and the location. The building is described with its organizational processes, usage intensity and spatial layout, the climate specifications, sustainability and energy efficiency requirements, and maintenance and management principles. The iSoR constitutes the main reference for commissioning the design team.

## 9.2 Climate Control Strategies

The choice of a climate control strategy is primarily based on an analysis of the interaction between the outdoor climate with the building envelope, and the building envelope with the indoor climate. Sometimes this indoor climate is influenced by internal moisture and/or heat loads (e.g. climate systems or people). The final risks to the collection and/or the building is a result of the use of the collection and the building.

The outdoor climate is a given and depends on the geographical location. In many countries national meteorological institutes measure the temperature, relative humidity, cloud cover, rainfall, wind speed, air pressure and sun activity of the outdoor climate. Sometimes the historic climate can be downloaded with daily averages going back several decades.

For evaluating a new design often a reference year is used. In the Netherlands the standard NEN 5060:2008 is used. It provides an artificial yearly climate as a reference for the technical installations advisors. But due to ongoing climate change it is advisable to take the expected climate changes into account when designing for the future. The northern hemisphere is predicted to become slightly warmer with an increase in the number of heat waves and heavier rain falls. This means by using a reference year that does not reflect the future climate, the results for the indoor climate will be less accurate.

The building envelope constitutes a barrier with a dampening and delaying effect between the outdoor and the indoor climate. By skillfully using the building mass, insulation properties and natural ventilation it is possible to positively influence the indoor climate passively, see also Chap. 7: Step 6. Before any mechanical system is considered, the options for optimizing the building physics should be carefully analyzed. The way the building is used will also have a significant influence on the indoor climate. People and equipment affect the indoor climate by releasing heat, moisture, volatile compounds, and $CO_2$.

Developing a climate control strategy includes the following steps (see also Fig. 9.1 for a schematic representation):

1. Take advantage of the physical properties and architectural features of the building, as well as of other existing possibilities in the current situation (e.g. sun-blinds and natural ventilation), to regulate the indoor climate.
2. Investigate the possibilities of implementing complementary structural and physical measures to the building.
3. Consider a ‘box-inside-a-box’ construction.
4. Consider placing objects inside showcases or microclimate enclosures. The climate inside the showcase or enclosure can be controlled passively or actively.
5. Keep in mind the building’s use, and the impact of user dynamics/behavior on the indoor climate. Consider, for instance, hanging wet coats in a separate area, not allowing large groups of people to remain inside small collection spaces for long periods of time, and avoid or limit ventilation with outside air during heat waves (or very cold days). In such situations, consideration should be given to adjusting the use of the building and for example, the number of visitors.
6. Finally, introduce climate control system (if necessary) as an addition to the preceding points. The type and size of the installation depends on each specific situation. A feasibility study provides an indication of the (most appropriate) installation concept and associated costs.

**Fig. 9.1** Six steps to develop a climate control strategies

## 9.3 Adapting the (Historic) Building

One way of improving the indoor climate is to improve the thermal and hygric performance of the historic building itself.

### *9.3.1 Architectural Engineering Measures*

Before choosing among different possible climate control concepts it is important to ensure that the building envelope delivers its basic function of making the interior impermeable to water and for the northern hemisphere, also wind. Attention should be paid to the maintenance of gutters, the quality of masonry, and the wind and water impermeability of roofs, windows and doors.

There is a balance between the architectural interventions and the technical implications of installing a climate control system. For spaces with (very) limited use, such as permanent storage, passive control of the building's moisture and temperature balance is surely an option (Padfield 2007). For zones with (very) intense use, such as exhibition rooms with high visitor numbers, often a ventilation system is used to bring in fresh air. If a strict indoor climate is required but the building physics is far from optimal, a large energy consuming climate control system will transport huge amounts of air to try to produce the required indoor climate. The most likely outcome is an indoor climate that shows large gradients in the rooms and (large) fluctuations in time. If however the building physics is very good, one can maybe do without mechanical climate control or with just a small mobile device that only operates during peak loads. In Fig. 9.2 the most likely quality of climate control is expressed as a function of the quality of the building envelope and the climate control system complexity. It can be readily seen that control of the indoor climate is quite challenging when the quality of the building envelope is poor, regardless of a small or large climate system (Martens 2012).

### *9.3.2 Improving Original Windows*

The location, size, profile, materials and construction of windows are important characteristics of a building. The (cultural) value of a building will depend on these and therefore one should be critical about changing the appearance of a window and/or its construction. Especially since optimizing windows generally involves more than just adapting the glazing. Reducing infiltration through seams between the frame and the wall and/or increasing the insulation properties is also sometimes required.

Reducing the penetration of solar radiation into the interior of the building hugely affects the stability of the indoor climate (see Chap. 7). Installing sun blinds on the outside, as can be seen in Fig. 9.3 is the best options, but not always possible. This measure will change the façade and thus the aesthetic value of the building.

This change of cultural value of the outer façade is often a reason for some national heritage institutes to be reluctant in issuing a permit for the placement of external sun shades onto monumental façades.

Many historic buildings are, or were, equipped with shutters. These have traditionally been used to protect the interior against sunlight and intruders. The outer

| | | Climate control system complexity | | |
|---|---|---|---|---|
| | | Low | | High |
| Quality of building envelope | High | Purpose built museum building with local heating and/or airconditioning<br>*Good indoor climate control*<br>*Low energy consumption* | Purpose built museum building with small equipment, such as moveable (de)humidifiers<br>*Good indoor climate control*<br>*Moderate energy consumption* | Purpose built museum building with HVAC<br>*Good indoor climate control*<br>*High energy consumption* |
| | | Modified (historic) building with local heating / airconditioning<br>*Moderate indoor climate control*<br>*Low energy consumption* | Modified (historic) building with small equipment, such as moveable (de)humidifiers<br>*Moderate indoor climate control*<br>*Moderate to high energy consumption* | Modified (historic) building with HVAC<br>*Moderate indoor climate control*<br>*High energy consumption* |
| | Low | Historic house with local heating / airconditioning<br>*Poor indoor climate control*<br>*Low energy consumption* | Historic house with small equipment, such as moveable (de)humidifiers<br>*Poor indoor climate control*<br>*Moderate to high energy consumption* | Historic house with HVAC<br>*Poor indoor climate control*<br>*High energy consumption* |

**Fig. 9.2** The indoor climate as a function of building physics and complexity of the climate control system

panels can be closed to reduce heat loss or gain when needed, e.g. during the day in hot climates or at night in cold climates. If shutters were fitted to the building in the past but have been removed, new shutters can be reinstalled and maybe thermally upgraded. If there are no shutters, thick curtains, which were common in historic buildings, provide a good and often cheaper alternative (Baker 2008). Even with these interventions the appearance of the building can be retained or often just slightly altered. An alternative to reduce heat loss is to install secondary glazing on the inside. This limits both heat and noise and increases safety. A major advantage is that the (historic) window can be maintained and that the secondary glazing can be removed easily. In cold climates it is advised to ventilate the volume between the two glazing panels with outside air, to prevent condensation.

Because the visual impairment of the façade, caused by installing external sun shading or by replacing authentic glazing, is often unacceptable, filters are frequently used. There are different types of filters available that can reduce heat transfer (infrared reflecting filters) or visible light transmission (daylight dampening filters) through windows. Since the ultraviolet radiation (UV) in sunlight represents a particularly high risk of chemical damage to museum collections, UV filters are also used. These filters block 99 % of the radiation between 300 and 400 nm, while 85 % of the visible light is transmitted.

**Fig. 9.3** Mesdag Museum; fixed external sun blinds (Photo: Schonewille, Central Government Real Estate Agency)

The visible light transmittance can be reduced by grey filters. These daylight dampening filters allow a fixed percentage of daylight to penetrate, e.g., with 10 %, 20 %, 30 %, 40 % or higher attenuation. They often have a grey color so that the spectral distribution of the transmitted light is not (significantly) affected. The use of filters causes the temperature of the glass onto which they are applied to rise, increasing the risk of breakage. Another aspect to note is the external appearance of the building that will significantly change when applying grey filters. Therefore it is advisable to apply the filters to all windows rather than one or two key rooms.

Infrared reflecting filters reflect and/or absorb the invisible, infrared part of the solar energy. They reduce the amount of energy that, upon entering the building, would cause an increase in temperature (known as the greenhouse effect see Chap. 7: Step 6). Such a reduction in heat load alleviates the need for compensation by a climate control system. Thus reducing the required climate control capacity to be installed, and possibly lowering the dimensioning of air conditioning systems. Infrared reflecting filters nowadays reflect less daylight (less than glass), and absorb less heat thus reducing the chance of thermally induced breakage in comparison to earlier films. Reflective coatings can reduce the heating from solar radiation by 60 to 80 %. Since these filters are highly reflective, the glazing of the building will act as mirrors, significantly changing the building's appearance. For historic buildings this is often an unwanted side effect. Careful selection of filters beforehand combined with mock ups of the selected filters in situ will help reduce solar gain while maintaining the buildings appearance. It is possible to use UV, daylight, and infrared suppression or reduction individually or jointly. It is recommended to ask for expert advice in advance about the choice of radiation reduction strategy, as well as the suitability of the glass support concerning its possible expansion due to heat absorption.

Sometimes the glazing is replaced by (very thin) insulation glass that can be fitted into the (historic) frames. Nowadays modern glass is available that resembles historically blown or pulled glass, this can be used so that the façade maintains its visual characteristics. High performance glazing, commonly known as double glazing, are double or triple glass window panes separated by an air or other gas filled space to reduce heat transfer.

In Fig. 9.4 several options to reduce the impact of the outdoor climate on the indoor climate through windows, are presented in six steps. These steps increase in terms of making changes (to cultural values).

### *9.3.3 Adding Secondary Glazing*

As secondary glazing increases the temperature of the inner glazing, the risk of condensation usually decreases. Depending on the degree of ventilation of the space between the additional internal or external glazing and the original pane, there may be more condensation on the inside of the added glazing, see Fig. 9.5. Often there are problems, such as drying and peeling paint, due to overheating between the original window and the added window. Another important point is that in cold climates the original single pane acted as a dehumidifier, in case of high indoor moisture loads. As a result of changes or adaptations made to the single glazing, the moisture balance of the building can be changed. By thermally upgrading the glazing system visible condensation on the window panes will be reduced. Where high internal moisture loads are still present this means that condensation, or high surface relative humidity, will occur on other cold parts of the building rather than the window panes, which might be not as visible to the human eye. As a result of the reduced condensation, the high moisture load in the indoor air will be maintained for a longer period of time. This can be beneficial but it will also result in higher relative humidities near outer surfaces of the building, leading to building decay. The condensation problem has just been shifted elsewhere.

### *9.3.4 Insulating the Building Envelope*

The use of insulation lowers the heat gain from, or loss to, the outside. Energy costs are reduced and thermal comfort is improved. There is, however, a risk of consequential damage if the building parts are inexpertly insulated. For instance, (often invisible) cold bridges can be introduced, or interstitial condensation can occur in the construction (see also Chap. 7: Step 6). From the building physics point of view, external insulation should be preferred. However, this is usually impossible because

1

**Refurbish window**

- Repair joinery
- Square up frame
- Replace windowsill and outer section
- Replace window pane and putty
- Fill gaps with wood or epoxy

2

**Draughtproof window**

- Seal seams and cracks between window and frame
- Seal seams and cracks between frame and building

3

**Re-use historic thermal improvements**

- Consider using shutters, blinds, etc…
- Consider using curtains, etc…

4

**Add new thermal improvements**

- Consider using shutters, blinds, etc…
- Consider using curtains, etc…
- Consider secondary glazing
- Consider filters
- Combination of the above

5

**Replace or improve glazing system**

- Thin double glazing (pulled or blow outer leave)
- Single glazing with low-e coating on the inside
- Laminated glas panes
- Vacuum glas panes
- …

6

**Replace or improve windowframe**

- Consider window frames with thermal break
- …

**Fig. 9.4** Six steps to optimize a window to reduce the impact on the indoor climate

**Fig. 9.5** Condensation with subsequent damage of the wooden window frame (Photo: Schonewille, Central Government Real Estate Agency)

of the unacceptable change to the historic appearance of the building. Internal insulation or cavity wall insulation is therefore often the only alternative.

Frost damage to the external façades is a possible effect in cold climates, due to a temperature decrease on the outside of the façade combined with reduced drying of its internal surface. Conversely, in the summer, the outer side of the façade becomes warmer and therefore more exposed to temperature stresses (Fig. 9.6).

### *9.3.5 Reducing Infiltration*

To reduce the influence of the outdoor climate on the indoor climate, is to reduce the amount of outside air entering the building. By means of ventilation, air enters the building with a certain temperature and absolute humidity. As long as this results in the required indoor air temperature and relative humidity this is okay, but most of the time this will not be the case. In hot and humid climates this air is too warm and too humid, while in the northern hemisphere in winter the entering air is too cold. Since the indoor temperature is often different from the outdoor temperature, the relative humidity will also change. Cold outdoor air will be heated, which will result in a low relative humidity. While in hot and humid climates, the indoor air is sometimes cooled, resulting in a high relative humidity.

The overall effect is that the indoor climate will be different from the indoor climate specified in the iSoR. By reducing the amount of outdoor air entering the

**Fig. 9.6** This a former prison built in the seventeenth century now houses the contemporary art museum (MAC) in Olinda, Brazil. The windows are permanently open and the tiled roof allows warm air to disperse through to the outside

building, this influence will be reduced. Indoor climates that primarily rely on climate control systems, will especially benefit from a lower air exchange rate.

### A Case Study of Recirculation

**Climate control in a small historic studio using 100 % air recirculation** (Maekawa and Conrad 2010).

**Introduction**

The Studio of Exhaustion from Diligent Service in the Qianlong Garden of the Forbidden City, Beijing, China was constructed in the late eighteenth century as a retirement lodge for the Qianlong Emperor, who reigned from 1735 to 1796. The west wing of the building contains a theatre. The east half of the building contains miscellaneous smaller rooms and a mezzanine level. The building is unique due to the high quality and diversity of arts and crafts used in its construction, decoration and furnishings. In the reception area polished wood, stretched embroidered silk (some authentic, most are modern copies), bamboo thread marquetry with carved jade insets and bamboo

(continued)

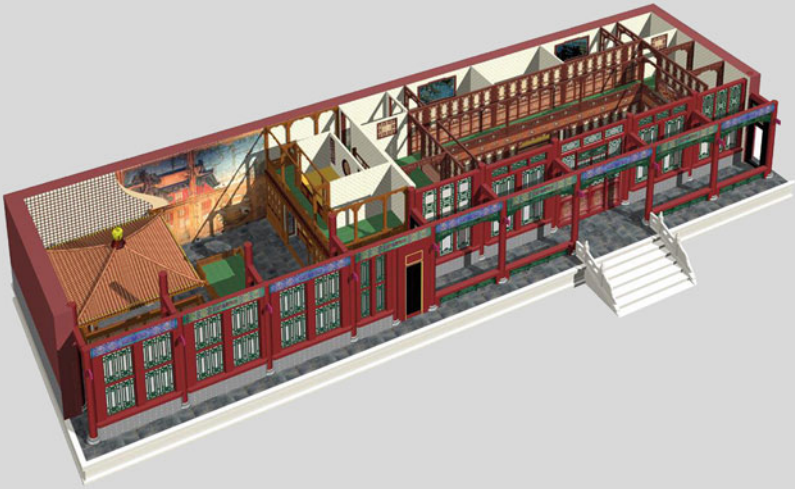


**Fig. 9.7** The studio of exhaustion from diligent service. On the *left side* the theater with mural paintings on silk and the wood resembling bamboo. On the *right side* the entrance to the reception area containing the embroidered silk and the bamboo veneers (Drawing: Prof. Liu Chang of the Tsinghua University in Beijing)

veneers can be seen. In addition, rooms have landscape paintings and works of calligraphy mounted directly on the wallpapered walls. The theater has a roofed stage with a dramatic two-story viewing area; mural paintings on silk, which cover the entire walls and ceiling; and wooden surfaces painted to resemble bamboo. It also contains unique and exquisite silk trompe l'oeil paintings on the ceiling and walls. After the decline of the Qing Empire, the building was abandoned and its interior elements were left exposed to the elements for several decades.

**Problem statement**

The Forbidden City would like to give (limited) access to visitors to enjoy the beauty of the retirement lodge and experience royal life in the late eighteenth century. Long term preservation of the building with its valuable decorations is of great importance.

High humidity in the building due to the combination of a hot and humid (Monsoon) summer and a relatively cool interior generates an environment with a high risk of mold. The infiltration of outdoor pollution and subsequent deposition on internal surfaces increases the risk of chemical decay and discoloring of the decorative surfaces (Fig. 9.7).

**Value assessment**

The serenity and quietness of the Qianlong Garden within the Forbidden City forms an enormous contrast to the other parts of this important monumental site. The studio is a wonderful example of royal social life which gives

(continued)

**Fig. 9.8** The theatre in the studio of exhaustion from diligent service with the mural paintings on silk (**a**) and the bamboo veneered panels in the reception area (**b**)

it a high social value. The retirement lodge is directly related to the Qianlong Emperor which gives the building a high historic value. Most of the interior decorations are unique and of very high quality with very high aesthetic value. The building, with its internal finishes and furniture is a unique example and allows the visitor a very enjoyable and meaningful experience of royal life within the Forbidden City. The interpretive capacity of this ensemble is high (Fig. 9.8).

Collection needs

Large (seasonal) relative humidity fluctuations are considered to give a high risk of mechanical damage to the wallpaper paintings, the bamboo veneers and the stretched silk. Based on research performed by the Smithsonian Institute (Mecklenburg 2005) it was found that nearly all of the decorated interior surfaces can be seriously damaged by condensing moisture. High surface relative humidity is to be prevented.

Due to an increased risk of mechanical damage from embrittlement at low temperatures, interior temperatures should be kept above freezing during the winter time. This will minimize physical damage to the painted surfaces. An annual relative humidity range between 30 % RH and 65 % RH is considered an acceptable risk and reasonable for the building and its collections.

Building needs

Originally part the building did not have glass panes within the window openings, which allowed natural ventilation. Installing glazing affected the infiltration of outside air and the air circulation within the studio. Especially in summer time when outside air is relatively hot, the inside air becomes relatively cold, and an elevated relative humidity inside can be expected. This increases the risk of mold. Air circulation is thus identified as very important.

Thermal comfort

Human comfort was identified as a lower priority than preservation of the heritage assets, therefore temperatures are allowed to fluctuate, according to the outside air temperature. This means that in wintertime indoor

(continued)

temperatures can drop below what is considered comfortable for people and in summer cooling is activated when outdoor temperatures are above 27 °C.

Understanding the indoor climate

The relatively simple building is constructed of wooden beams, with a masonry infill and a tiled roof. The lower part of the south wall (entrance side) consists of wood panels and a door. The original openings above the wooden walls have been enclosed with glass windows. These wooden walls are approximately 75–100 mm thick. The wooden walls and windows provide good insulation. Interior heating combined with humidification could increase the risk of condensation on the inside surfaces of both windows and walls. The building allows air to enter through the gaps present due to the warped entrance doors and the roof construction. Due to infiltration it is expected that the building will adapt quickly to the outdoor temperature. The indoor relative humidity is largely dependent on the air exchange rate.

Control strategy

Between 2006 and 2009 the studio was restored. Visits are limited to small groups only. The restoration involved improving the building envelope by reducing infiltration and improving thermal insulation by installing double glazed windows. Sun screens are located between the glass panes. Climate control was realized by a small unit containing a direct expansion (DX) cooling coil, a hot gas-heating coil and supply and return ducts, to allow dehumidification (by means of cooling with subsequent re-heating) and cooling. There is no humidification or heating of the inlet air.

To reduce the infiltration of outdoor pollution the air is filtered with three filters; a pre-filter, an intermediate filter, and a HEPA filter. The relatively small unit is placed in the attic and the ducts, air supply opening and return air grilles are all placed out of sight, without changing the aesthetic value of the decorated surfaces.

The aim of climate control is to reduce the deposition of outside particulates on the decorative surfaces to a minimum. As well as to reduce the risk of mold by maintaining a relative humidity below 55 %, and to reduce the risk of mechanical damage by maintaining a relative humidity between 40 % and 55 %.

The inside air is unheated, but can and will be cooled when the outside temperature is above 27 °C. Even though the outside temperatures and relative humidity can be quite extreme, with hot and humid summers and cold and dry winters, the inside climate was maintained between 40 % and 55 % relative humidity during the first year of operation.

### *9.3.6 Use of Buffering Materials*

At constant absolute humidity, the relative humidity of the air in a given space will decrease as the temperature increases and vice versa. If hygroscopic materials such as wood or paper are present, the relative humidity variation will be partially dampened by the buffering effect of these materials. As the relative humidity changes, they will absorb or release moisture accordingly. It is possible to maintain the relative humidity at almost constant levels, under fluctuating temperature conditions by introducing enough buffering materials in a small and controlled air volume. Such an effect is commonly observable in measurements carried out in libraries and archives housed in historic buildings, due to the presence of significant amounts of paper. If the room contains an exceedingly large amount of hygroscopic materials in relation to its volume, it is possible that the relative humidity increases when the temperature rises (like in a microclimate box heated by the sun). At higher temperatures, the equilibrium moisture content of hygroscopic materials decreases and they release moisture to the surroundings. As a result, the absolute humidity of the air, and therefore, sometimes also the relative humidity, increases.

Internal insulation made of capillary-active, diffusion-open calcium silicate was installed in the New Rijksmuseum in Amsterdam. This kind of insulation gives higher indoor surface temperatures, resulting in lower relative humidity levels at the wall surface. As a result it prevents surface condensation behind paintings, furniture or showcases hanging on, or close to the wall, since they will act as a thermal layer between the indoor climate and the outer wall. If condensation occurs, the condensate will be readily absorbed by the calcium silicate due to the high water absorption coefficient of the insulation material. Because of its low vapor diffusion resistance factor the drying of the wall to the indoor is possible.

## 9.4 From ‘Low’ to ‘Ultra-low’ Energy Storage

In the past few decades the research group from the National Museum in Copenhagen, together with colleagues from other museums in Denmark, have been searching for ways to reduce the energy consumption of storage facilities, without compromising the climate needs for the collection, by optimizing the building physics. Determining the buffer capacity of building materials, measuring and evaluating existing archives and stores, modelling new designs and actually developing those facilities, demonstrated the possibilities and challenges of reliable collection preservation without full climate control by HVAC systems. During this research the focus has been on:

1. How to design buildings that benefit from the outdoor climate in Northern Europe, with a yearly temperature fluctuation of 0–30 °C;
2. How to maintain a relative humidity indoors that is approximately stable within an acceptable level of risk of mechanical damage;

3. How to cope with climate standards that prescribe a constant indoor temperature and relative humidity.

Based on hygrothermal modelling of the building it could be concluded that an almost airtight building with some thermal mass, combined with moisture buffering could maintain an acceptable climate and use ventilation with outdoor air, only at moments when the absolute humidity of the external air is beneficial to further stabilize the indoor climate.

These ideas were put into practice designing the archive of the Arnemagnaean Institute in Copenhagen University (Padfield and Larsen 2005). Being located in an office building led to a more or less steady indoor office temperature (20–24 °C) on one side of the archive and fluctuating outdoor temperature (0–18 °C) on the other. The lower outdoor temperatures were used to cool the airtight archive (applying a carefully calculated thin insulation layer on the outside) and preventing heating by the office temperature (applying a thick insulation layer). A moisture buffer was applied to the wall, which further helped to stabilize the indoor relative humidity.

Since this design was quite contradictory to traditional building designs, the builders made some mistakes; the insulation package between in- and outside was thicker than designed and the moisture buffer was not able to adsorb and desorb water vapor due to the application of two layers of acrylic paint. Climate measurements helped identify these issues. It clearly showed that designing buildings with a very special and stable indoor climate is possible. However, it requires not only a proper understanding of the outdoor climate and the building physics but also proper coordination in the building process and evaluation during operation.

The temperature buffering capacity of common building materials, such as brick, earth, concrete and stone, were used to show that the inside surface could have a small daily temperature cycle, displaced by 12 h when compared to the much larger outdoor temperature fluctuation. The importance of thermal mass was further illustrated by analyzing the climate in the archive of the fortress of Segovia in Spain (Padfield et al. 2007). It is suggested that next to using the thermal inertia, the indoor climate can be further stabilized by either reducing ventilation (since infiltration is already nil) or by increasing the relative humidity buffering capacity of the building materials.

In temperate climates, heating can be used to reduce the relative humidity. This concept is called conservation heating and was amongst others applied in the Suffolk Record Office in Ipswich. The building is heated in winter and contains a large amount of moisture buffering materials allowing passive measures, especially as there is no air circulation. The winter heating and high buffering capacity ensures a more or less stable relative humidity so that heating is not required during the already relatively hot summer season (Padfield et al. 2007).

To reduce the risk of mold, ventilation has been advocated for centuries. But, ventilation reduces the performance of the humidity buffering, creating a conflict between optimal collection preservation and building performance. Evaluating the literature did not show that the risk of mold was affected by ventilation. So there was no mold prevention argument against reducing the ventilation to an absolute minimum if possible.

The low energy Centre for Preservation of Cultural Heritage in Vejle, Denmark consists of an airtight, light-weight building on an uninsulated concrete slab (Rasmussen 2007). The walls were painted white with a cement based paint of high permeability. The walls and roof are insulated on the outside. The concrete floor allows the ground heat to be exploited in winter and to be used as cooling capacity in summer.

Lower indoor temperatures are beneficial to the preservation of many objects. For cold climates the absence of heating will reduce energy consumption. During high outdoor relative humidity in summer, the indoor air is dehumidified. Calculations found that the air exchange rate must exceed six times per day before conservation heating becomes cheaper than dehumidification. If the air exchange rate is zero, dehumidification costs nothing, after the initial drying of the building and its contents. In practice, it is possible to get the air exchange rate in a storage building down to less than once per day. The two low energy stores described rely on a very low air exchange rate with the outside, and a fairly low re-circulation rate within the store.

To stabilize the indoor relative humidity a proper moisture buffering building material should be applied to the inside wall. Several materials were tested to find the most suitable one (Padfield and Jensen 2011).

When the performance of the climatized Royal Library in Copenhagen, the Arnamagnæan archive and the museum store in Ribe are compared, it can be concluded that the passive storage facility of Ribe scored very well (Ryhl-Svendsen et al. 2010, 2011). The lightweight, but insulated and airtight building of the low energy storage facility in Ribe is dehumidified in summer. The indoor temperature follows, with reduced amplitude, the outside temperature. Daily temperature fluctuations are completely evened out by the thermal inertia and thermal insulation. The ground is also used as a thermal buffer, moderating the yearly climate cycle.

## 9.5 From Building Level to Object Level

To separate the climate around objects from that of the room, a climate control system can be combined with the use of showcases. The air inside the showcases can either be actively or passively conditioned. Passively conditioned showcases or microclimate boxes dampen the surrounding climate fluctuations by buffering the collection materials inside (Padfield 1996; Brimblecombe and Ramer 1983). Existing showcases can be adapted for this purpose if necessary (Thickett et al. 2008). The quality of the climate inside the passively conditioned showcase is determined by the capacity of the hygroscopic materials inside the showcase, the (room) temperature and its fluctuations and the air exchange rate of the showcase. Airtight showcases, without internal heat sources, will maintain a more stable relative humidity than leaky systems, with internal heat sources, such as lighting.

Well-sealed showcases have a typical ventilation (air exchange) rate in the order of 0.1 exchanges per day, while ordinary showcases will have an exchange rate of about one exchange per day. Extremely leaky showcases can sometimes replace their entire volume more than ten times per day. If the air temperature inside the showcase is exposed to the influence of heat, e.g. due to internal halogen lamps, the relative humidity can fluctuate enormously (Camufo et al. 2000). The climate inside the showcase can then constitute a much higher risk of damage than the prevailing climate in the room.

Two points should be noted here. The air exchange rate results from the combination of all possible transport mechanisms (infiltration, diffusion and permeation), among which the most efficient transport results from temperature and pressure differences (Michalski 1994). Pressure differences inside a showcase occur as a result of changes in the air pressure outside the showcase and local temperature differences. The presence of heat sources inside the showcase will therefore promote air exchange with the room. Although tightly closed showcases are in many ways better than leaky ones, the risk of accumulation of gaseous pollutants is higher in the former with respect to the latter. For this reason, showcases should be manufactured with inert materials such as glass and metal, which do not off-gas harmful contaminants.

There are different possibilities to actively control the climate inside showcases. Temperature control is not straightforward and relatively expensive. Since the risk to the collection results primarily from an incorrect relative humidity, temperature control is much less effective in reducing climate risks. Commercially available low-capacity humidifiers and dehumidifiers can be used to modify the relative humidity of small volumes of air to the desired levels. Because the collection should not be directly exposed to the airflow of the equipment, the way of introducing the conditioned air into the showcase must be well thought out. Another aspect is the risk of large relative humidity fluctuations due to equipment malfunction. In order to reduce this risk it is possible to pass the air over or through hygroscopic buffering materials prior to introducing it into the showcase.

Research has shown that microclimate boxes or enclosures are very effective in dampening (external) relative humidity fluctuations. Their effectiveness against temperature fluctuations, however, depends on the type of temperature fluctuations or gradients. Uniform heating caused by an increase in the room temperature (convection) is adequately compensated for by a sufficient moisture buffering capacity. Occasional local heat transfer by radiation, e.g. due to direct sunlight, will lead to large temperature gradients inside the microclimate box (Ankersmit et al. 2011). Experiments on pastels showed that a short exposure of the microclimate box to infrared radiation caused rapid local heating inside the box and consequently moderately large relative humidity gradients, see Fig. 9.9. After 30 min exposure, the temperature difference between a black (continuous line) and a white (dashed line) painted area of the same pastel had increased to 6 °C (10.8 °F) with a corresponding relative humidity gradient of 13 %. The relative humidity difference between the black area (continuous line) and the cardboard behind it (dotted line) was even larger. Depending on the amount of hygroscopic

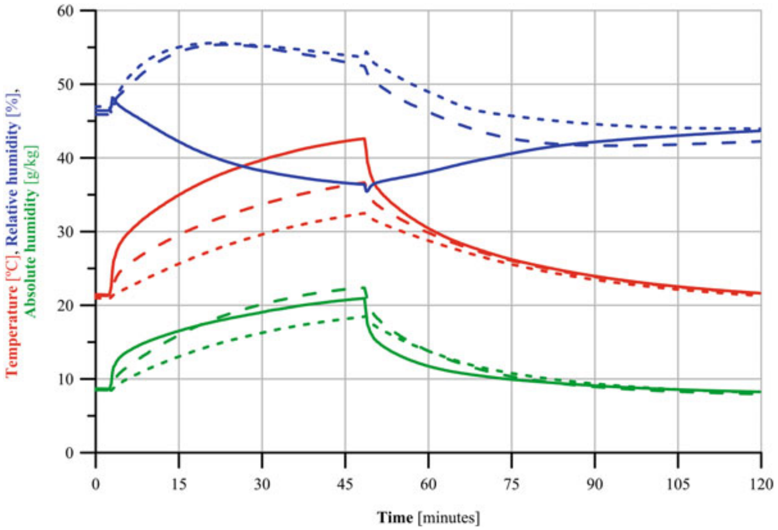


**Fig. 9.9** The relative humidity, absolute humidity and temperature profiles inside a microclimate box and behind a pastel when exposed to infrared radiation. *Continuous line* shows the climate behind the black painted surface, the *dashed line* the climate behind the white painted surface and *dotted* the climate in the air pocket near the cardboard drawer

material within a microclimate system, similar relative humidity gradients and subsequent moisture transport from warm to cold spots can be expected when framed objects are hung on cold walls or exposed to direct sunlight or high intensity incandescent spotlights. Padfield et al. (2002) has previously described the mechanism for these observations and Ligterink and Di Pietro (2007) have developed a model to predict local relative humidity and absolute humidity at different temperatures zones in closed air volumes. To minimize the risks from relative humidity fluctuations to sensitive objects, like pastels in microclimate frames, one should:

- Reduce the transport of air into the box by making the box as airtight as possible
- Keep the volume of the microclimate box as small as possible
- Add hygroscopic material to the internal volume
- Prevent (strong) temperature gradients caused by local heat and/or cold sources close to the pastel or microclimate box. For pastels in original framing exhibited in historic houses on cold/warm outer walls, spacers can be placed between the object and the outside wall, or the object should be placed elsewhere.

High temperatures inside a microclimate box are most likely to increase the risk of emission of fatty acids (palmitates, stearates) from paints, which can subsequently be deposited onto the glass cover, generating a mirror image. Since darker paints generally contain more binding media and less fatty acid-reactive inorganic pigments, this effect is more pronounced for darker parts (Schilling et al. 1999). Fresh paints, such as areas of retouching, also constitute a higher risk concerning this type of emissions.

## 9.6 Climate Control Concepts

Air conditioning consists of several basic functions: heating, cooling, humidification, dehumidification, ventilation, and air purification (filtering). These functions can be realized through various alternative technical concepts. More than 50 different installation concepts are presented in the Handbook of technical installations (ISSO 2000a). A distinction between three functions is made concerning air conditioning concepts:

- Central generation of heat, cold, dry, or moist air, mainly by a mechanical device.
- Distribution of air and/or water by pipes and ducts in shafts, re-use of flues, transport areas, etc.
- Release by radiators, post-conditioning cooling and heating units, air in- and outlets, nozzles, etc.

Criteria are needed to be able to choose between the different installation concepts. The most important criteria for selecting a climate control installation for a historic building with a museum function are (in no particular order):

- Affordability of the initial investment and the long term running costs (total cost of ownership);
- Knowhow and capacity within the organization to understand and operate the systems, especially in case of calamities;
- Availability of space for central engineering (mechanical room) and post-conditioning units;
- Availability of space for air ducts and water pipes;
- Availability of space for placing equipment on walls, ceiling, and floor;
- Preferably no water pipes in storage areas and exhibition rooms;
- Preference for mixing ventilation with high-induction diffusers, in view of uniform temperature and relative humidity distribution in the exhibition rooms. Cooled air requires a different blowing pattern than heated air; therefore, preferably, use of automatically adjustable grilles;
- Reliability: automatic switch to a safe mode upon malfunction, with automatic notification to the facility management and/or maintenance team;
- Robustness of components: use components that are of high quality;
- Availability of components: use components that are commercially available, custom made products can be quite expensive, especially to replace;
- Low energy consumption;
- Simple in design, understandable to operate, and robust with respect to maintenance.

Using these criteria, a rationalized choice can be made among the various alternatives. The different types of use for spaces in the building should be taken into account, e.g., exhibition room, reading room, research room, conservation-restoration workshop, auditorium, restaurant, offices, etc. For rooms and zones where objects are frequently or permanently present, the climate conditions should be based on the conservation criteria defined in Chap. 3, step 2. The situation is different for rooms/zones occupied only by people. The desirability and possibility of creating zones with different climate conditions should therefore be considered. This can often (and sometimes must) be integrated with safety measures such as accessibility and fire compartmentalization.

### *9.6.1 Introducing Active Climate Control*

The indoor climate is maintained within the allowable limits of temperature and relative humidity for a chosen climate class, by means of a climate control system. As before a number of basic functions can be distinguished herein, e.g.: heating, cooling, humidification, dehumidification, ventilation, and air purification (filtering). These basic functions can be combined and designed in different ways. Commonly used (limited) climate control strategies include (in increasing degree of complexity):

1. Natural ventilation by openings in the building envelope and/or temporarily opening windows and doors.
2. Idem 1 plus heating using radiators/stoves equipped with a thermostat.
3. Idem 2 plus mobile humidifiers and/or dehumidifiers.
4. Idem 1 plus hygrostatic heating.
5. Idem 4 plus mobile humidifiers and/or dehumidifiers.
6. Mechanical supply and exhaust (balanced ventilation), preheated air ventilation and heating using radiators equipped with a thermostat.
7. Idem 6 plus limited central cooling of the ventilated air.
8. Idem 6 plus central pre-cooling and steady post-cooling per zone and/or room. The cooling and heating systems are connected to each other to avoid simultaneous heating and cooling. Heating and cooling elements are usually combined in one device such as a fan coil.
9. Idem 6 plus central humidification and dehumidification through air ventilation.
10. Idem 7 plus central humidification and dehumidification through air ventilation.
11. Idem 8 plus central humidification and dehumidification through air ventilation; climate control per zone or room with priority for maintaining the (desired) relative humidity (Full climate control).
12. All-air system with mechanical supply and exhaust (balanced ventilation), and heating, cooling, humidification, and dehumidification through air only; climate control per zone or room with priority for maintaining the (desired) relative humidity.

The degree to which the above-mentioned measures are able to achieve and/or maintain a certain climate class obviously depends strongly on the quality of the building envelope. It is also clear that the complexity and size of the air handling unit, and thus also the costs, increase as the level of indoor climate control increases. Especially since the need for air purification by filters becomes more important when most air enters the building through the air handling unit (Table 9.1).

Actively conditioned showcases are equipped with their own climate control system, which often regulates only the relative humidity, and are thus more or less independent from the surrounding conditions. Full climate control inside showcases is not yet extensively used in museums. Some large museums, like the British Museum in London, experimented with acclimatizing display cases. Some showcases are fitted with humidifiers and/or dehumidifiers, or microclimate generators, to control the internal relative humidity. In some galleries, multiple showcases requiring the same RH level are fed from one central unit.

In the Royal Ontario Museum in Toronto, showcases have been connected to microclimate generators (MCG) that allow de/humidification (Coxon 2007). The ducts run below the floor, sandwiched between layers of concrete. A slight positive pressure within the cases prevents air to leak into the display cases from the gallery. It was found that the distance between the MCG and the showcases and the number of angles in the piping significantly reduces the airflow into the show case and therefore the climate around the objects on display. When in 2007 the Maritime Museum in Amsterdam began renovations of the historic VOC warehouse dating from 1656, it was decided to take a similar approach to climate control for the objects (Lony 2008, Lony et al. 2010). The air conditioning strategy of the museum was twofold: a semi-museum climate for the galleries and museum climate inside the showcases. The floors were raised to house the ducts. Conditioned air was supplied to more than 200 display cases. The reason to choose elevated floors was to keep the historic ceilings intact and in sight and prevent major changes to the historic building.

In the library of the Casa de Rui Barbosa Museum, Rio de Janeiro, Brazil the balance between visitor comfort and collection conservation in a historic building was found by optimizing the original building physics and enhancing them with a mechanical ventilation system. These enhancements improved the climate not only in the library but in the attic and cellar spaces as well. Supply ventilation and dehumidification units were connected to the library room by ducts with diffuser grilles on the library floor. The diffusers allow for a large airflow with minimum vertical air velocity (Maekawa 2007).

Active climate control inside a display case does not always require the showcase to be attached to a duct system. In the South Tyrol Museum of Archaeology in Bolzano, Italy the remains of the 5,000 years old so-called ice man are displayed. The mummy is displayed in a climate that closely resembles the environment of the find; a temperature of −6 °C (21 °F) and a relative humidity of 98 %. The clothing and equipment made of organic materials that were found are also displayed, under tightly controlled environments. The display cases are individually equipped to control the relative humidity and temperature, see Fig. 9.10.

**Table 9.1** Overview of climate control strategies and corresponding basic functions

| | | Thermal | | Hygric | | Ventilation | | Control | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Heating | Cooling | Humidification | Dehumidification | Natural | Mechanical | Thermostatic | Hygrostatic | Building control system |
| 1 | Natural ventilation | | | | | √ | | | | |
| 2 | 1 + radiators | √ | | | | √ | | √ | | |
| 3 | 2 + mobile de/humidification | √ | | √ | √ | √ | | √ | √ | |
| 4 | 1 + hygrostatic heating | √ | | | | √ | | | √ | |
| 5 | 4 + mobile de/humidification | √ | | √ | √ | √ | | | √ | |
| 6 | Mechanical supply and exhaust, with pre-heating and radiators | √ | | | | | √ | √ | | |
| 7 | 6 + limited central cooling | √ | √ | | | | √ | √ | | (√) |
| 8 | 6 + limited central cooling and local post-cooling | √ | √ | | | | √ | √ | | (√) |
| 9 | 6 + central de/humidification | √ | | √ | √ | | √ | √ | √ | |
| 10 | 7 + central de/humidification | √ | √ | √ | √ | | √ | √ | √ | (√) |
| 11 | 8 + central de/humidification, climate control per zone, and priority for maintaining relative humidity | √ | √ | √ | √ | | √ | √ | √ | √ |

(continued)

**Table 9.1** (continued)

| | | Thermal | | Hygric | | Ventilation | | Control | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Heating | Cooling | Humidification | Dehumidification | Natural | Mechanical | Thermostatic | Hygrostatic | Building control system |
| 12 | All-air system with heating, cooling, de/humidification through ventilation air, climate control per zone, and priority for maintaining relative humidity | √ | √ | √ | √ | | √ | √ | √ | √ |

**Fig. 9.10** The air conditioning of individual showcases in the south Tyrol museum of archaeology

The risk of a short and severe fluctuation due to the climate control system malfunctioning is higher in actively controlled showcases then in passively controlled cases. Especially as conditioned air is inserted in the immediate vicinity of the objects. It is advisable to take preventive measures such as automated closing valves or automated shut down of the HVAC upon malfunctioning.

### *9.6.2 Limited Climate Control Systems*

There are different types of mobile climate control systems, which are presented below in increasing order of complexity.

#### Mobile Humidification

Mobile humidifiers supply water vapor to the air of the gallery directly (see Fig. 9.11). As a result, the absolute humidity increases and, at constant temperature, so does the relative humidity until the desired set point is reached. This type of

**Fig. 9.11** The Frans Hals Museum in Haarlem uses several mobile humidifiers to increase the indoor relative humidity during winter and dehumidifiers to reduce it in summer

equipment is already widely used in museums, and can be placed without great effort or investment. Electricity and water supply are nevertheless required, which in some cases may require changes to the building. Water supply is provided through connection to a water pipe (with overflow protection), or by means of manually filling the internal reservoir (typically 20 l).

Two types of mobile air humidifiers can be distinguished: the adiabatic humidifier, and the isothermal humidifier. The former is further subdivided into evaporative and ultrasonic humidifiers. For evaporative humidification warm air is pushed through a wetted filter, after which the air is slightly cooler and humidified. Ultrasonic humidification is based on the addition of small droplets of moisture into an air flow. The droplets subsequently evaporate in the air. Isothermal humidifiers work on the principle of humidification by steam. The capacity of these systems differs with the type and varies from approximately 0.5–2.5 l of water per hour.

Mobile humidifiers are switched on and off by either a built-in or an external (mounted elsewhere in the room) humidistat. The humidistat needs to be regularly calibrated and checked to ensure proper operation. Besides, the filters should be regularly cleaned or replaced. In practice, the maintenance of humidifiers has been shown to receive insufficient attention from building and collection managers.

### Mobile Dehumidification

Lowering the relative humidity at constant temperature can be achieved by removing moisture from the air. This also requires the availability of electricity. Mobile dehumidification units can be divided into two types: refrigerant and desiccant dehumidifiers. These mobile units have a limited capacity, which means that their deployment should preferably be done in more or less closed spaces (compartmentalization). Care should be taken to avoid dry air being driven directly over the objects (e.g. by not placing the dehumidifier under a table), or that the unit operates too close to a heat source. Attention should also be paid to the occurrence of microclimates, and to possible critical locations for placing the unit such as in corners or in the vicinity of cold bridges.

Refrigerant dehumidification is a type of dehumidification that condenses the moisture from an air flow on a refrigerated coil with a small fan. This works as long as the temperature of the coil is below the dew point of the air. Condensation-based (refrigerant) dehumidifiers generally show the best performance under humid (RH >45 %) and warm conditions. In humid but cooler indoor climates, however, their use becomes non-optimal.

Desiccant dehumidification uses a desiccant, a special humidity-absorbing material, which is exposed to a humid air flow. The saturated absorption material is then rotated into another air flow where it is dried, typically by heating it. This will recharge the desiccant, which is subsequently rotated into the humid air flow again. And so on.

A hybrid system combines condensation and desiccation-based dehumidification. In both types of dehumidifier condensed moisture is removed, either automatically through a drain hose, or by manually emptying the container in the base of the unit.

### Hygrostatic or Conservation Heating

In 1987 the National Trust investigated the possibilities of energy efficiency in three historic houses where relative humidity control was done by dehumidifiers (Staniforth and Hayes 1987). Leaky spaces in which the air exchange rate is high, due to chimneys and cracks around doors and window frames are often impossible to seal from the outside. Experiments were performed to control the relative humidity by temperature control. Thermostats allowed raising the internal temperature approximately 5 °C above outdoor conditions, so that the relative humidity could be maintained within the target bandwidth of 50–65 %. It was in this article, in 1987, that the term conservation heating was first used.

So when thermal comfort is not a priority, hygrostatic heating – instead of the more common thermostatic heating – can be an option. By adjusting the temperature, the relative humidity can be controlled or stabilized. In order to lower the relative humidity the air is heated until the relative humidity reaches the desired set point. Conversely, when the relative humidity is too low, the air is not heated (which does not automatically means that the relative humidity will rise, as no water is added, but it will prevent the relative humidity from dropping any further). Since the 1990s the National Trust has developed its use and it has become their main method of controlling the relative humidity in most of their properties (Staniforth et al. 1994). It has been found in the UK that generally the relative humidity can be kept close to 60 %, by maintaining the inside temperature 5–6 °C above the outside temperature. With a maximum temperature of 18 °C regardless of the relative humidity (The National Trust 2006).

The simplest form of conservation heating is an electric heater, such as an oil filled radiator, connected to a hygrostat that switches on and off. When radiators are already present in the building the thermostat can be replaced by a hygrostat.

This particular approach has a limited scope of application. Hygrostatic heating clearly provides a lower level of thermal comfort to visitors, since during the winter a lower temperature is often maintained and conversely the air can be heated in summer. In other words, the room can become warmer in the summer (so that the relative humidity does not increase) and colder in the winter (so that the relative humidity does not decrease). This can be an option for museums and historic buildings that are closed in winter or have only limited winter use, which is often the case with National Trust houses in Great Britain.

Using this system is not without risk. A minimum set point temperature is required in cold climates to avoid freezing of water pipes, while a maximum set point is necessary to avoid overheating in summer. Another potential problem is the presence of large amounts of hygroscopic materials in a closed space, e.g., a historic library in a poorly ventilated room. In situations like this, the moisture balance can behave contrary to the expected effect (Padfield 2007). The use of some degree of humidification/dehumidification can offer a solution in these situations. A temperature increase to reduce the relative humidity, will reduce the lifetime of chemically instable materials (Michalski 2002).

The options to control the indoor climate in warm and humid regions are somewhat limited because of the average high and relatively constant temperature and relative humidity. In the late 1990s the Getty Conservation Institute (GCI) initiated research into the development of strategies to preserve collections in hot and humid climates. The focus was on sustainable climate control strategies that significantly reduced the biological risks to collections. Based on climate measurements and careful analysis of the building physics specific solutions were developed to balance the acceptable risks to the collection and comfort for occupants.

Ventilation, controlled by humidistats and a convective heater based climate control system were installed in two small rooms containing the Historic Archive of Cristóbal de La Laguna on the island of Tenerife. This system successfully eliminated relative humidity fluctuations above 70 % and stabilized the environment (Maekawa and Toledo 2003).

A similar design was installed in a museum store in Valle Guerra, Tenerife. This climate control system consists of three sets of supply and exhaust ventilation, five convective heaters, and interior and exterior humidistats, see Fig. 9.12. The relative humidity is successfully kept between 55 and 65 % throughout the year.

**Fig. 9.12** The museum storage in Valle Guerra, Tenerife showing a convective heater on the wall at the far end

## Cooling

When air temperatures are generally too high, active cooling becomes important. The first cooling units were developed in the early twentieth century to improve industrial efficiency (Brown and Rose 1996). Air was passed over chilled pipes to cool the air, resulting in condensation removing some water and decreasing the relative humidity. Nowadays air can be cooled in basically two ways: adiabatic cooling using the evaporation of water or diabatic cooling using either direct systems, such as direct expansion used in split-units (Fig. 9.13) or indirect systems, such as cooled water used in HVAC-systems.

Cooling is typically realized using a refrigeration cycle by circulating a coolant, typically water or a glycol/water mixture from a warm zone to a cool zone. A refrigerant is pumped into the evaporator coil (Fig. 9.13a), which is located in the warm zone which needs to be cooled. The low pressure causes the refrigerant to evaporate and absorbing heat it will thus cool off. At the opposite side of the cycle is the condenser. This is generally located outside at the warm zone (Fig. 9.13b). Here

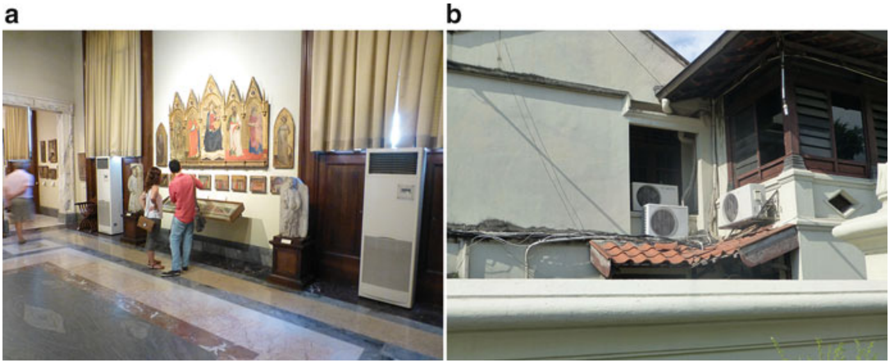


**Fig. 9.13** A typical local cooling unit with the evaporator (evaporator coil, expansion devise, and blower) on the inside (**a**) (Roma, The Vatican Museums) and condensing unit (condensing coil, compressor and fan) on the outside (**b**) (Jogyakarta, Museum Sonobodoyo)

the refrigerant vapor is compressed and forced through another heat exchange coil, condensing the refrigerant into a liquid, thus releasing the previously absorbed heat from the cooled zone. The air stream passing the cooling coil in an HVAC system or a split-unit will cool down. Since the running temperature of the cooling coil, especially in hot and humid regions, will be below dew point. Moisture will be generated. The cold air that is blown into the zone will have a relatively low relative humidity. Surfaces placed in this air stream will become significantly colder, even to a point below the dew point temperature causing surface condensation. Placing objects near or in this air stream should be avoided at all times.

### *9.6.3 Full Climate Control*

To control the indoor climate in a zone to climate classes B, A, and AA, full climate control with increasing precision in controlling the relative humidity and temperature, coupled with a degree of control over air ventilation, filtering, and distribution of the entire space is required. This is achieved by an HVAC (heating, ventilation and air conditioning) system. In order to select the most appropriate system it is necessary to consider the sensitivity of the collection (objects and building), as well as the suitability to the (historic) building as described in Chaps. 4, 5, and 6 (steps 3, 4 and 5). An important aspect of implementing full climate control is that, the indoor climate becomes disconnected from the outdoor climate. The climatic conditions should be maintained 24 h a day, 365 days a year to prevent climate-related risks to the collection. This is in contrast to the visitor's comfort, for which the desired conditions are maintained only during opening and office hours. Consideration should be given to these aspects when choosing the type of HVAC and the method of ventilation.

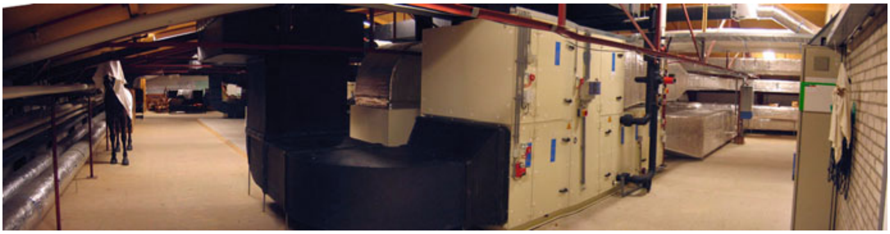


**Fig. 9.14** Air handling unit in a mechanical room

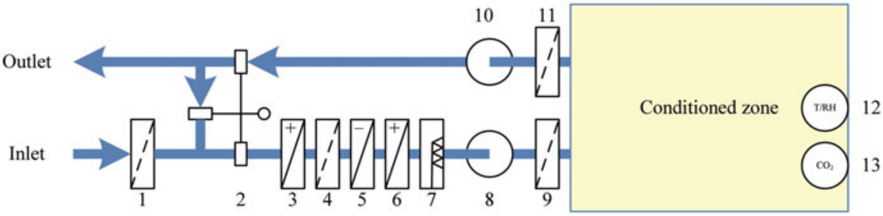


**Fig. 9.15** Schematic representation of a climate control system, including: (*1*) Coarse-grade filter (F7); (*2*) Motorized mixing valve; (*3*) Pre heater; (*4*) Chemically active filter; (*5*) Cooler/dehumidifier; (*6*) Heater; (*7*) Humidifier; (*8*) Supply fan; (*9* and *11*) Fine-grade filter (F9); (*10*) Extract fan; (*12*) Temperature and relative humidity sensors; (*13*) $CO_2$ sensor

Housing an HVAC often requires a great deal of space, such as illustrated in Fig. 9.14. A mechanical room is required to place boilers, water heaters, chillers, and air handlers. This room needs to be easily accessible for maintenance, taking into account the transport routes for large equipment parts. The area should be well protected against fire and water leakage. All seams should therefore be properly sealed. Devices with an increased risk of leakage should not be installed above historic interiors or important collections, the unit should be installed above collecting trays with a drain. A water detector with automatic signaling to the administrator should be placed on the floor of the mechanical room.

Water-carrying systems such as water-based radiators, water cooled devices, and mobile equipment connected to a water supply in exhibition areas deserve extra attention in relation to leakage hazards.

One of the available concepts for full climate control in exhibition areas is an all-air system. This means that the desired climate conditions are achieved exclusively by the introduction of (pre-conditioned) air. A typical air conditioning installation consists of an air handling unit, ducts to and from the exhibition areas to distribute the air and air in- and outlets. The air handling unit has different components to generate the desired air conditions. A schematic representation of the construction of a typical air handling unit is shown in Fig. 9.15.

Outdoor air is drawn into the system and filtered by a coarse-grade filter (F7) (1) to remove large particles. It is then mixed with recirculated air (2), preheated (3) and filtered (4) by a chemical filter. The air is subsequently cooled

(5) either to reduce air temperature and/or to remove moisture, reheated (6) and then conditioned to the desired relative humidity (7). Chemically active (4) and fine-grade filter (F9) (9) are typically used to remove fine particles and volatile pollutants. Air is moved by means of fans (8, 10). All systems are temperature controlled (12). Most systems also are controlled by the relative humidity (12). For human comfort and energy savings some systems are controlled by measuring the carbon dioxide levels (13).

Air recirculation is an important aspect of climate control in museums. Part of the air coming from the conditioned space is reused by the central air conditioning unit. The ratio of ventilation to recirculation is adjustable in most installations, according to the outdoor air conditions and the number of people in the building or space. Under extreme outdoor conditions, e.g. during a heat wave, it is advisable to minimize ventilation, i.e. almost 100 % recirculation. When the outdoor temperature is between approximately 15 and 18 °C and the indoor temperature is too high, it can be more interesting in terms of energy savings to ventilate more and thus take advantage of the cooling effect of the outdoor air, instead of the cooling unit within the air handling unit.

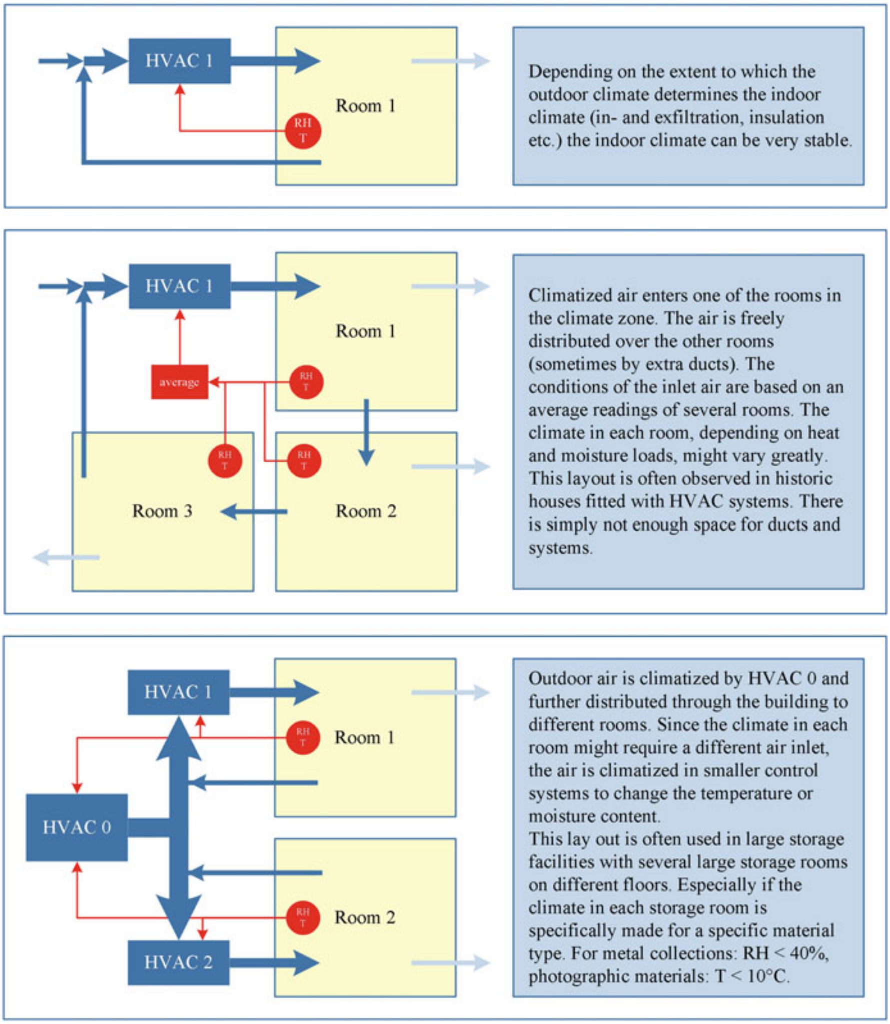
There any many types of air conditioning systems, and a significant variation concerning the operating principle of their components. In the scheme shown in Fig. 9.15, for instance, the coarse-grade filter (F7) in the return line could optionally be removed. Heat and moisture recovery devices are also missing in the scheme. The use of a thermal wheel with moisture recovery can be economically advantageous in situations where large volumes of outdoor air are fed into the system. ISSO publication 43 (ISSO 2000a) describes many of these concepts. Given the complex nature of climate control projects, it is recommendable to involve a climate advisor in the early stages of the design process so they can become familiar with operations within a museum. In order to help facilitate communication with a climate advisor, a description of the application, operating mode, and components of an all-air system is presented as an example.

The quality of climate control depends on the layout of the building and the collection rooms and the capacity of the HVAC system or systems. In Fig. 9.16 a scheme is presented to illustrate the relationship between these parameters.

## Air Distribution Principles

When using an all-air system, care should be taken to ensure that the air is sufficiently mixed. This means that conditioned air should be introduced in the room with a high induction (mixing capacity). A proper flushing of the space, by which homogeneous conditions are created, is a requirement. The choice of an appropriate type of air inlet, such as a swirl diffuser, is therefore important. The location of the supply air outlets should also be well planned. In some situations it is possible to use already existing ducts and channels, see Fig. 9.17.

An all-air system provides the means to heat, cool, humidify, and dehumidify a zone using exclusively the (conditioned) air. For the selection and positioning of the



Depending on the extent to which the outdoor climate determines the indoor climate (in- and exfiltration, insulation etc.) the indoor climate can be very stable.

Climatized air enters one of the rooms in the climate zone. The air is freely distributed over the other rooms (sometimes by extra ducts). The conditions of the inlet air are based on an average readings of several rooms. The climate in each room, depending on heat and moisture loads, might vary greatly. This layout is often observed in historic houses fitted with HVAC systems. There is simply not enough space for ducts and systems.

Outdoor air is climatized by HVAC 0 and further distributed through the building to different rooms. Since the climate in each room might require a different air inlet, the air is climatized in smaller control systems to change the temperature or moisture content.
This lay out is often used in large storage facilities with several large storage rooms on different floors. Especially if the climate in each storage room is specifically made for a specific material type. For metal collections: RH < 40%, photographic materials: T < 10°C.

**Fig. 9.16** Schematic presentation of the climate control strategy with one or more HVAC systems to control the indoor climate in one or more zones

supply air diffuser it is important to take into account that cold air falls and hot air rises. This can result in undesirable temperature stratification, whereby excessive temperature differences can occur in the room.

The mixing of warmer and cooler air can be improved by using mixing supply nozzles. A mixing supply nozzle is a small, powerful air jet with a high inducing capacity. The advantage is that large volumes of surrounding air can be set into motion by using small amounts of supplied conditioned air. Air supply at floor level should be avoided to prevent dirt deposited on the floor from (re)mixing with the air

**Fig. 9.17** The air inlet hidden in an existing fire place with nozzles to provide a good mixing

introduced in the room. Furthermore, blowing air directly onto the collection should be avoided. Gradients in temperature and relative humidity should be prevented.

A constant air flow rate (constant air volume or CAV-systems) is preferable over a variable air flow rate (variable air volume or VAV-systems). VAV-systems have proved their worth in buildings other than museums. These systems are of limited or no use in museums due to poor relative humidity regulation, insufficient air flow, maintenance sensitivity, and insufficient flexibility to meet the desired climate conditions (ASHRAE 2011). The ratio ventilation: recirculation in areas where large numbers of visitors are expected can be adjusted with assistance of a $CO_2$ sensor. Once the preset $CO_2$-concentration threshold is exceeded, larger volumes of fresh air get automatically introduced in the mixture.

Another mixing principle is the so-called displacement ventilation. In this strategy relatively cool conditioned air is supplied at floor level into the zone. This cool air spreads over the floor and rises as the air is slowly heated due to heat exchange with the air in the zone. An upward convective flow is created (also called thermal plumes) that reach to the ceiling where it is extracted. Because of this thermal gradient, and therefore a gradient in the relative humidity, the use of displacement ventilation is inadvisable in a museum environment (Neuhaus et al. 2010). Known disadvantages of displacement ventilation are:

- Vertical temperature gradients are created causing local differences in relative humidity;
- Possible cold air flows near the floor;
- Heating the room with supply air is not effective: hot air rises up and does not circulate.

### Ventilation Rate

The volume of fresh air to be introduced (ventilation) can generally be kept very small for collection conservation purposes. In working areas, the Occupational Health Guidelines in the Netherlands describe that, on average, approximately 35 $m^3/h$ of fresh air per person has to be supplied. In public areas, the volume of fresh air to be supplied can be adjusted according to the expected number of visitors. The volume of the space should be taken into account in these cases, since visitors' impact on the air quality is obviously greater for smaller spaces.

If air is also used for heating and cooling as well as to provide ventilation, then a larger volumetric flow rate is required. In these cases, part of this larger air flow is recirculated. The total volumetric flow rate is therefore partly composed by ventilation, and partly by recirculation. The ratio between the two components is usually adjustable and depends on the number of people present. Less ventilation usually means less energy consumption. When the outdoor conditions are favorable it might be beneficial in terms of energy savings to temporarily ventilate more – a point of interest to operation and management. For instance, in exhibition rooms with high heat and cooling loads, and with a strict demand on temperature uniformity in time and space, the total air volume is circulated between six and eight times per hour. In well attended exhibitions the ventilation rate will increase by up to 50 % depending on visitor numbers. This is high in comparison to office installations where, depending on the concept, the total air volume circulates from one to three times per hour. In museum spaces with limited heat and cooling demands, less recirculation will suffice. In these cases, more attention should be paid to the spatial temperature uniformity. Temperature differences can be reduced by improved air mixing with individual fans or through adapted air supply using, e.g. swirl diffusers or high induction air jets. In such situations, the air velocity in the proximity of objects should be taken into account.

### Central Humidification

There are basically three different types of humidification systems, steam, ultrasonic and evaporative humidification. Each system has its advantages and disadvantages. Steam humidification consumes more energy and therefore has higher energy costs than ultrasonic or evaporative humidification. Ultrasonic systems often have higher maintenance costs. Especially since ultrasonic systems require demineralized water with a conductivity of approximately 8 μS. Demineralization is done by a set of semi permeable filters. Another possible disadvantage of steam humidifiers is that, the steam is chemically treated with additives that may be hazardous for the collection. It is advisable to use evaporative humidifiers eventually in combination with limited steam humidification. Maintenance of humidification equipment should be established by a protocol and strictly fulfilled.

The humidification installation should be designed so that stagnant water is avoided in the system to prevent the growth of *Legionella* and other microorganisms. All materials used in a humidification installation should be selected in order that microbiological growth is not promoted (ISSO 2000b).

### Central Dehumidification and Cooling

A significant problem in museums and libraries is often the insufficient or inefficient dehumidification of air. If only limited dehumidification is required, this can be achieved by centrally dehumidifying the inlet air through cooling to (below) its dew point. This cold air should preferably be post-heated per building zone. If large amounts of dehumidified air are required, e.g. due to high infiltration rates of outdoor air in leaky historic buildings, the dehumidification capacity can be increased by increasing the amount of supplied air, which will require a larger installation. The possibilities of installing large air ducts in historic buildings are limited in view of aesthetic boundary conditions.

### Air Filtering

Introducing large amounts of outdoor air into collection areas would significantly increase the risk of pollutants if this polluted air is not filtered. Filtering of supply air is therefore essential to reduce the concentration of soot, especially in urban areas and primary pollutants such as $SO_2$, $NO_x$ and $O_3$ in industrial areas. The filters should be installed in such a way that no unfiltered air can circulate beyond them. Air filtration can be divided into different stages depending on the type of filters used, e.g.:

- Coarse-grade,
- Fine-grade,
- Electrostatic,
- (Activated) carbon, and
- Chemically active filters.

Pre-filtration is necessary to prevent internal contamination of the air conditioning installation. It also increases the lifetime and functionality of gas and fine-grade filters. Particles captured by coarse-grade filters (G4) have typical dimensions of 3–10 μm. In order to remove at least 50 % of the particles in this class, it is advisable to use at least a F7 (EU7)-type filter. With the use of fine-grade filters in the class from F9 (EU9), the smallest particles down to 0.3 μm are removed. Carbon and chemically active filters should preferably be used only in spaces without, or with only a small, public presence (e.g. storage areas) and in airtight spaces.

## 9.7 Measurement and Control

Unlike systems designed for office buildings, which primarily regulate the temperature and the amount of fresh air, air conditioning systems for museum environments should primarily be designed to control the relative humidity. The way to achieve this is to control the properties of the air for example the temperature [°C] and the absolute humidity [%] (Fig. 9.18, green). But since hygroscopic or

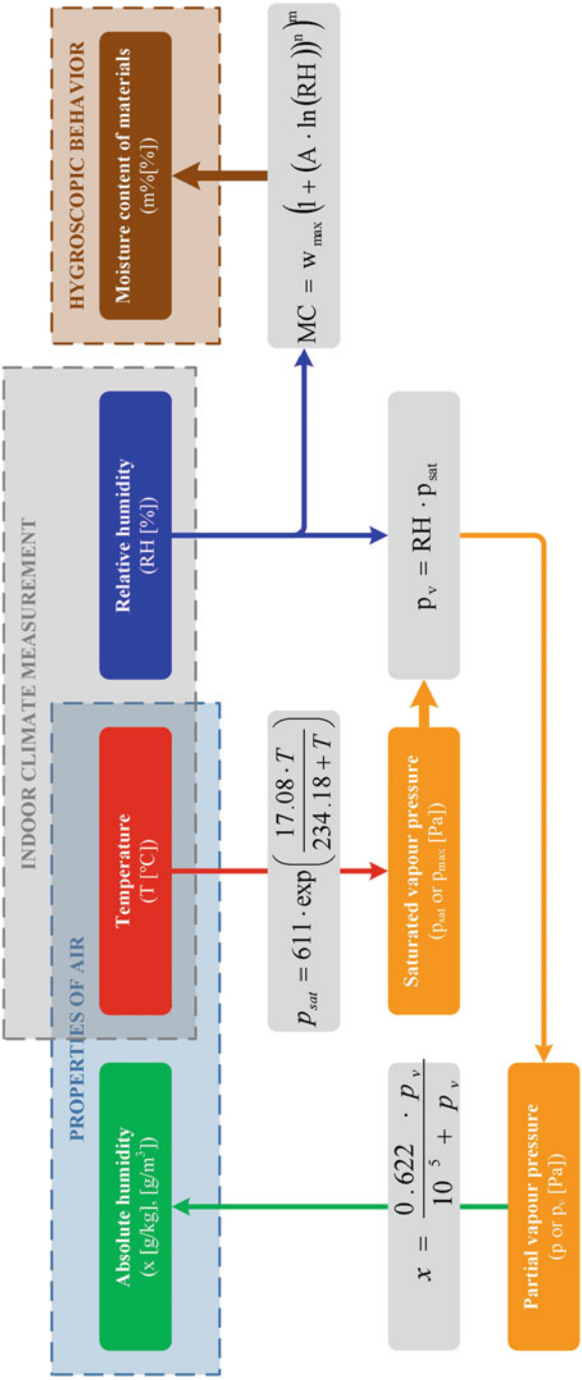


**Fig. 9.18** The properties of air and their relationship with measurement and hygroscopic behavior of materials

mechanical behavior is not related to absolute humidity but to relative humidity (Fig. 9.18: brown) the system has to measure the temperature and relative humidity at room level (Fig. 9.18: blue) and calculate the absolute humidity. By comparison with the desired temperature and absolute humidity, the latter is also calculated based upon temperature and relative humidity. The control systems then need to be capable of determining whether to humidify or dehumidify the supplied air.

The dependence of relative humidity on temperature is hereby disconnected in terms of control engineering. This improves controllability and leads to more stable conditions and a better control of the relative humidity. Another important point to consider is the desired level of precision for temperature and relative humidity control. The design of climate control installations and the costs involved depend strongly on this aspect, and the use of industrial control equipment deserves consideration. The installation, including its control system, should be able to regulate and monitor humidity, temperature, volumetric flow rates and pressure drops across filters, as well as to signal and report the occurrence of malfunctions.

Temperature and humidity sensors should be placed in representative locations in the exhibition areas, and not in the return line of the air conditioning installation. The sensors should be periodically checked for proper operation and calibrated whenever a deviation is observed. The technology of wireless sensors is currently reliable. It is advisable to use these sensors in areas with frequently changing exhibitions. In practice, it is common for fixed sensors in such areas to disappear behind walls or to be destroyed as a result of refurbishment or changes in the room (e.g. when walls are repainted).

### 9.7.1 Delivery and Warranty

All components of a climate control system should be checked for proper functioning upon delivery, which should be recorded in testing and measurement reports. All installation drawings and process diagrams should be fully updated according to the situation upon completion. In case of power failure, the installation should switch to a stable and safe idle mode. Emergency power units should maintain the vital functions of the system, which should be able to restart in a controlled way upon recovery of the power supply.

Upon delivery, the user receives a manual with operation instructions for the climate control installation. A 1-year warranty is (typically) provided by the installation contractor. It is recommended to sign a contract with the installation contractor for its monitoring, operation support, and performance optimization. The proper functioning of the installation under varying climate conditions should be verified during the (1-year) warranty period. The previously agreed performance levels should be controlled for each season. The installation settings are also optimized during the warranty period. Its performance should be continuously monitored (and adjusted) by the contractor using an independent monitoring system. This allows a timely and adequate response in case of failure and structural defects. Regular reporting and discussion of results help guarantee the optimal operation of the installation.

### 9.7.2 Maintenance and Management

All documentation is finalized at the end of the (1-year) warranty period. The revised documents are transferred to the installation owner for management purposes. The owner should sign a maintenance contract. These are often short-term contracts where obligations are assigned such as the change of filters, control and care of equipment, and cleaning of parts. For museums with complex installations it is advisable to make long-term performance contracts in combination with an obligation of best intents. In practice, it is essential that the maintenance obligations and the quality of the service are regularly inspected and controlled. This prevents complacency by the maintenance service provider. Make sure that spare parts are available on site or readily available from suppliers.

Practice has also indicated that the climate control installation and its expected performance should be permanently monitored by an installation management system (IMS)[1] starting immediately after the warranty period. Independent measurements outside the IMS can provide valuable information. These measurements can be performed internally by experienced technical staff (if available) or otherwise externally by a service provider. Based on their results it is possible to timely and adequately react in case of malfunction and deviations of a structural nature. Regular reporting and discussion of results help guarantee the optimal operation of the installation.

In addition to the technical monitoring via IMS it is of great importance that the collection manager and the maintenance department of the museum independently check the quality of the indoor climate (or hire someone do it) on a regular basis.

### 9.7.3 Equipment Failure Protocol

If one of the components of a climate system malfunctions, temperature and relative humidity can easily fall outside the desired range. Two types of malfunctioning can be distinguished (Neuhaus 2012).

The first is a short term malfunctioning of a component. As an example, a steam humidifier that stops adding moisture to the air stream in an HVAC system that conditions 100 % outside air. During winters, the outside air contains very small amounts of moisture, without humidification, relative humidity fluctuations of 25 % can occur within a few hours. Temperature and/or relative humidity changes can

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[1] In the United Kingdom this is also called a building management system (BMS).

also occur when HVAC systems are shutdown during maintenance. These fluctuations can be prevented if annual maintenance is planned during seasons when the outdoor specific humidity is similar to the indoor specific humidity.

The second type of malfunction can be described as a long term erroneous functioning of the HVAC system. This can often be attributed to ineffective monitoring of the functioning of the system, or ineffective monitoring of the indoor climate conditions by staff or maintenance personnel.

The response time of most objects in mixed collections is longer than a few hours. These objects can get through failures of the climate control installation without the risk of being mechanically damaged, if failure is repaired within these timeframes. Certain objects, however, have shorter response times and therefore will be at risk on the occasion of short-duration failures of the climate control installation. Often these susceptible objects are protected by microclimates, such as boxes and closed frames. The response time of the most sensitive and valuable parts of the collection should be included in the iSoR, as well as the time within which someone (staff, contractors, etc.) is required to react in the eventuality of failure of the climate control system, and the time within which the malfunction must be corrected. The concept installation designer should weigh possible system failures against the sensitivity of the collection, and factor in what precautions should be taken to minimize downtime and therefore the risks of damage to the collection. For instance, spare parts could be locally stored to allow for immediate replacement whenever necessary, and a good protocol with clearly defined roles and responsibilities should be available for dealing with malfunction warnings.

The set points for alarms should be chosen sensibly. In many larger institutions the alarm goes off so often that maintenance contractors stop investigating them within weeks. Therefore it might take days before a collection manager or other person checks the climate data and is able to evaluate the condition of valuable and suscpetible objects in the collection.

Accessibility for maintenance, and risks to the collection in the event of malfunction or leaks are often neglected, important aspects. Water and steam pipes above and in the exhibition areas could possibly leak, as could air handling units. This should be avoided as much as possible, and/or the system should be equipped with leak detection, or a provision to contain/collect water leaks. It is advisable to carry out a risk analysis, or review the existing one, whenever changes are made in the climate control installation, and to update the protocol accordingly.

### *9.7.4 Operating Costs*

Maintaining a stable indoor climate that is suitable for museum collections is often very expensive. In most cases, however, the increase of the useful life of the collection easily justifies the annual costs of maintaining the desirable museum indoor climate conditions.

Acquiring, implementing and using a climate control installation is not cheap; on average, a museum spends approximately 30–40 % of its total budget on climate control. It has been calculated that the average energy intensity of a museum is 15.7 KWh/visit, or 2.34 Kg $CO_2$ per visit (Farreny et al. 2012).

Research has shown that the costs of reducing relative humidity fluctuations increase exponentially as the allowable fluctuation range decreases (Mecklenburg and Tumosa 1995; Artigas 2007). Despite the large financial investments, none of the 20 Dutch museums measured was found to maintain the environment within ASHRAE climate class AA 100 % of the time (Martens 2012). So despite the climate systems constant operation and circulating air, it does not mean that the indoor climate is stable, and/or even close to the expected indoor climate (Ankersmit and Stappers 2011).

Model studies into energy saving strategies of traditional, or basic, HVAC systems indicated that a floating temperature set point, which depends on the outdoor temperature can generate a significant reduction in energy consumption, from 13 % (Ascione et al. 2009) to up to 70 % (Kramer et al. 2014; Yang et al. 2014). The use of a desiccant module, an enthalpy wheel, and controlled (minimal) ventilation further increase the annual energy cost savings by 15 %, 15 %, and 45 % respectively, when compared to a basic HVAC (Ascione et al. 2009).

In areas with significant seasonal temperature changes, geothermal heat pumps can be considered. This system uses the constant temperature of the earth as the exchange medium, similar to the Centre for Preservation of Cultural Heritage in Vejle, Denmark. Instead of using the constantly fluctuating outside air temperature, the relatively constant ground temperature which is warmer than the air during winter and cooler than air in summer, is used. Even though the installation price of a geothermal system can be several times that of an air-source system of the same heating and cooling capacity, the additional costs are returned in energy savings in approximately 10 years. The yearly costs of maintenance and energy consumption should be considered beforehand. Another underestimated risk of failure of indoor climate control is the human factor. There are great technical feats of design, which can fail because the staff do not have sufficient knowledge to operate the installation, let alone maintain or properly manage it. For this, extreme contracts are often signed resulting in an increasing distance between the museum staff and the indoor climate. In the worst case, the collection manager completely loses her/his ‘feeling’ about the indoor climate.

It is recommended to monitor energy consumption, and to analyze the results in order to assess the possibilities of implementing energy saving measures.

## 9.8 Conclusions

Introducing a climate control system and making structural and technical modifications in a building will never fully eliminate climate-related risks to the collection. Firstly, it may be expected that the installation will reduce short fluctuations to a minimum; however, given the physical aspects of the building, seasonal variations often cannot be completely prevented. Secondly, the risk of a sudden and severe climate fluctuation and the risk of small fluctuations increases when the indoor climate is entirely dependent on the installation. In case of equipment failure, just like when the outdoor climate is extremely hot or cold, the indoor climate can experience sudden and extreme changes, depending on the outdoor conditions. It is advisable to take measures to minimize this risk, which on the other hand can also introduce new risks.

## *9.8.1 Water and Condensation*

New risks introduced by a climate control installation include, for instance, water damage risks resulting from leaks in water-carrying pipes. It is also important to know if, and where, cold spots are present in the room (or in the building) when humidifying the air during the cold season or winter. If the surface temperature in these cold spots drops below the dew point, condensation will occur with all its consequences such as rot and mold. Measuring surface temperatures, e.g. with individual sensors or an infrared camera, can help clarify the risk of condensation and the (probable) extent of damage.

### Dust and Gaseous Pollution

The use of ‘free cooling’ through natural ventilation or night ventilation with untreated, unfiltered outdoor air is discouraged in the museum context. Outdoor air almost always has a temperature and relative humidity that differ from the desired indoor conditions. Moreover, the use of ‘free cooling’ can result in dust and gaseous pollution. ‘Free cooling’ is often the main cause of relative humidity fluctuations in museums and libraries.

The occurrence of gaseous pollutants in the indoor environment, through off-gassing and diffusion from new constructions, new furniture, and the evaporation of cleaning products, can constitute an unacceptable risk of chemical damage. Measures should be taken to control these gaseous pollutants in areas where sensitive objects belonging to valuable collections are kept. The main compounds that should be taken into account are acetic acid, formaldehyde, hydrogen sulfide, nitrogen dioxide, ozone, and sulfur dioxide. All these gasses are removed by molecular filtration. The choice of adsorbent material to be used depends on the target gas(ses) to be filtered out. Some gasses are simpler to remove with help of activated charcoal, while others can only be captured by using chemically treated carbon or potassium permanganate filters. Molecular filtration is expensive both in terms of acquisition and maintenance. The technique is therefore more applicable to situations with limited ventilation and limited presence of people, such as in storage areas and archives. In public spaces, e.g., exhibition rooms with infiltration of outdoor air through doors and corridors, the air purification efficiency decreases while the costs increase significantly. Use of molecular filtration in such situations is not recommended.

### Design Aspects

Finally, some points of attention for designers and managers are provided:

- For optimal collection conservation, very large relative humidity gradients should be avoided. This can be achieved by avoiding large temperature differences and gradients:
- Never expose objects to direct sunlight or other radiant heat sources that operate at high temperatures;
- Do not place objects in the proximity of radiators when at high temperature;
- Do not install heat-generating light sources, such as halogen lamps, inside or in the proximity of showcases;
- Do not place objects directly on or against cold walls, a distance of 8 cm between object and wall is advised;
- Do not expose objects (directly) to air conditioning draughts since the incoming air can be of different quality than expected;
- Operate climate control installations preferably stepwise, i.e. do not use ‘on-off’ operations.

The result of this step is a set of scenarios that will provide the climate specifications that are the result of step 7. Often, each scenario consists of a combination of physical building adaptations, combined with the use of micro climates and/or some kind of climate control measure. For each of these scenarios the costs for implementation and running, are to be identified.

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# Chapter 10
# Step 9: Weighing Alternatives

**Abstract** Two methods that help to make a decision are described. A simplified multi-criteria decision analysis allows criteria to be weighed with different units and a cost benefit analysis to weigh decisions based on monetary impact. A consequence matrix, in which the consequences of different climate control options for different objectives are analyzed, is presented. This approach gives an indication of which options help to develop the most objectives. A cost benefit analysis, in which monetary value is used to weigh alternatives is briefly described.

**Keywords** Making a decision • Weighing alternatives • Multi-criteria decision analysis • Cost benefit analysis

## 10.1 Introduction

People decide on the basis of maximizing their own expectations. Management decisions rarely depend on analytical and systematic evaluation of consequences and probability of occurrence. Making smart preservation decisions requires careful consideration of a set of trade-offs and uncertainties, as well as clear specification of the goals, objectives, and issues being addressed. Since this type of decision making is rather complex, often decisions are made much more opportunistically and intuitively.

Making decisions very often requires dealing with different, sometimes even conflicting criteria that need to be evaluated. Cost, or price, is usually one of the main criteria. Some measure of quality is typically another, which is often in conflict with the cost. In purchasing a car, cost, comfort, safety, and fuel economy may be some of the main criteria that need to be considered. Optimizing the indoor climate will probably require considering costs, sound, air movement, air quality and reliability.

In our daily lives, usually multiple criteria are weighed implicitly and we may be comfortable with the consequences of such decisions that are made based on only intuition. On the other hand, when stakes are high, it becomes important to properly structure the problem and explicitly evaluate multiple criteria. In making the decision of whether to build a nuclear power plant or not, and where to build it, there are not only very complex issues involving multiple criteria, but there are also

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multiple parties who are deeply affected by the consequences (Keeney 2004). Structuring complex problems well, and considering multiple criteria explicitly, leads to more informed and better decisions.

In this step the options that are developed, to realize the objectives, are evaluated. The relationships between climate control strategies and objectives should be analyzed in a systematic way, which allows an estimation of the strengths and weaknesses of control strategy alternatives. This will lead to a result that most likely enables you to realize the objectives defined in Chap. 2.

There are basically two methods to evaluate the options to reach a specific goal. Decision trees were developed to guide conservation or preservation decisions. Strang developed a tree to serve as a simple document to visualize the process used and knowledge needed to select and preserve modern information carriers, like magnetic disks, tapes etc. (Strang 2003). The major shift in the decision making to add an item to the archival collection is the criterion “If we can preserve it, we can collect it”. While traditionally the approach has been “collect it and hope we can preserve it someday”. Once the decision is made to collect the material, the actual preservation strategy is then selected by going through a set of questions.

The Foundation for the Conservation of Modern Art designed a decision making model for the conservation and restoration of modern art (Foundation for the Conservation of Modern Art 2005). This model helps organize the issues on condition and meaning, and weighs conservation options for preserving the meaning of a work. It can be seen as a decision making trajectory. It addresses the condition phenomenon; whether this phenomenon is a problem; and if so of what nature; it proposes various solutions; weighs the consequences of these solutions; and proposes a definitive conservation plan. A key element in the model is the question; “Is there is a discrepancy between condition and meaning?”.

The importance of decision diagrams was pointed out by Michalski and Rossi-Doria (2011). “*The diagrams not only illustrate the path to the final decision, but they make explicit all the paths that were considered but rejected. Ideally the reasons, or lack of reasons, for those rejections become explicit. It even shows the options that were not considered at the time*.”

In the paper discusses the path that was followed to derive at the optimum conservation treatment to consolidate flaking paint. The option of doing nothing was a serious alternative to more active options. The case study also illustrated that different conservators might choose very different options for treatment while still being completely objective in their judgments. The power of the mind-map is that it helps visualize the larger set of factors and relations that affect the decision.

Here two methods are presented that help make the decision: a cost benefit analysis and a simplified multi-criteria decision analysis that allows weighing criteria with different units. Both methods are used to analyze the ways specific climate control strategies help to achieve the objectives developed in Chap. 2: Step 1.

## 10.2 Cost Benefit Analysis

By weighing the pros and cons, i.e. benefits and costs, of a decision one tries to make the arguments that determine the outcome explicit. Comparing costs with benefits requires some kind of unit. In an economic cost benefit analysis, the costs and benefits are quantified and compared using currency. In cultural projects comparing euros or dollars spent and gained, is probably less common, especially since the relation between monetary value and cultural value is very subjective. A more common unit to evaluate climate control options would be to evaluate the amount of risk reduced for each euro or dollar spend. This requires a quantified risk analysis in which all climate related risks are identified, analyzed and evaluated (Michalski 2004).

### *10.2.1 The Costs*

The costs involved to manage indoor climate risks can be divided into: financial costs and the costs related to a loss of cultural values. The financial costs obviously involve purchasing the control system. When the control system is in use, sometimes extra monetary costs are involved for running the apparatus. So financial costs involve both purchase as well as running costs, the latter are also called structural costs. The costs related to the purchase of for example a climate control system can be calculated by breaking down the system into components, the costs for maintenance, costs related to optimizing the building, energy consumption and hours spent by facility staff.

The loss of cultural values, such as experience, architectural, authenticity and historic, are not as easily quantified. In Fig. 10.1 three examples of climate risk mitigating options are presented that all have a different impact on other objectives. Some options are not directly visible and are most likely only visible to the expert who knew the situation prior to the changes being made. Reconstructions and high quality finishes can offset the loss of authentic surface finishes to a very limited extent. The replacement of authentic historic windows and frames by modern glazing is a loss of value but how can this be expressed?

### *10.2.2 The Benefits*

The benefits of an option to reduce the risks to the collection would obviously be a reduction of the climate related risks to the moveable collection and building and/or an improvement of visitor comfort. But sometimes implementation of an option (from doing nothing to full climate control by an HVAC system) will have

**Fig. 10.1** Three ways to mitigate climate risks to collections that significantly influence the objective of visitor experience: (**a**) by placing a noisy humidifying machine close to the object, (**b**) by presenting objects behind Plexiglas, that yellows in time and (**c**) by controlling visitor flow that allows minimal time to enjoy and appreciate works of art

secondary benefits such as the image of the museum. In Table 10.1 some costs and benefits are identified.

For example, improvements in the indoor climate involves saving time to treat damaged objects. This saved time and materials used for treatment can be calculated as benefits. Obviously the material loss of the damaged cultural object(s) is less easy to assess.

If costs and benefits are expressed by currency, it is important to do that for a specific moment in time. Since one euro today does not have the same value as that same euro in 10 years' time. This is because a euro available now can be invested and earn interest for 10 years and would be worth more than 1 euro in 10 years. If the interest rate is $r$ then a euro invested for $t$ years will grow to be:

$$(1 + r)^t \tag{10.1}$$

Therefore the amount of money that would have to be deposited now so that it would grow to be 1 euro in $t$ years in the future is:

$$(1 + r)^{-t} \tag{10.2}$$

**Table 10.1** An overview of costs and benefits for climate control systems

| | Costs | Benefits |
|---|---|---|
| Climate control system | Implementation of system<br>Buying hardware<br>Software license<br>Extra staff<br>Training | Reduction of climate risks<br>No more mold<br>Increase in lifetime of materials<br>Reduction in risk of mechanical damage<br>Less money/time spend on conservation treatments |
| | Structural<br>Energy consumption<br>Maintenance<br>Time required by staff | Improvement in human comfort<br>More people have access to cultural values |
| Adapting the building | Construction activities (material costs)<br>Adapting building (insulation, zoning etc.)<br>Adapting (historic) glazing | Reduction of climate risks<br>Risk of biological decay reduced<br>Reduction of salt efflorescence<br>Reduction in risk of mechanical damage |
| | Immaterial costs<br>Loss of (historic) space<br>Loss of (historic) materials<br>Loss of experience value | |
| Maintenance | External maintenance contracts | |
| | Changing filters | |
| | Changing components (e.g. humidifiers) | |

This is called the discounted value or present value of a euro available in *t* years in the future.

## 10.3 Multi-criteria Analysis

A standard feature of multi-criteria analysis is a matrix. In this matrix, or table, the consequences of alternative options, here climate control strategies, are assessed. This is done by placing the objectives (see Chap. 6: Step 5) in the top row and putting the options in the first column, see Table 10.2.

The options can be developed in different ways. It is very helpful to think of the options in terms of opportunities. Since developing options is a creative process, brainstorming has been used for many years. Another way of creatively developing options is to follow the next steps:

- Individually develop solutions to achieve an objective;
- Bring together and compare all potential solutions. Discuss and investigate new options and present a total overview of all solutions developed;

**Table 10.2** An example of a fictional consequence matrix to evaluate options, here climate control strategies, against objectives

| | Objectives | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Minimize costs | Minimize the rate of deterioration | | Maximize access to (the cultural values of) the collection and building | | | Systems (i.e. means) objectives | | | |
| Control strategies | Total costs | Building | Collection | Experience value | Architectural value | Etc. | Robustness | Lifetime | Volume/ size | Access |
| Option 1 | | | | | | | | | | |
| Option 2 | | | | | | | | | | |
| Option 3 | | | | | | | | | | |

- Discuss the benefits of the best ideas. Ask why it is a good idea and investigate the pros and cons;
- Make short list of the options. This can be done by asking team members to assign a score, e.g. 10 points for the best option, 8 for the next best and 5 for the third one.

It is important to develop options in an open creative atmosphere. If the focus is too narrow, there is a tendency towards short term success rather than long term gain.

The short list can then be used to weigh against the objectives. Obviously different viewpoints might arise. Sometimes this is due to a lack of information, or the effects of the options are not properly explored and more research is required. But to encourage the team members to investigate all options, they can be asked to indicate if they are strong supporters, undecided or that they think the option is completely unacceptable. This way, all involved are encouraged to explain why they have a specific opinion and an open discussion can help to find consensus. The question 'what is needed to clarify the confusion?' can be especially helpful.

For each mitigation strategy and for every objective, we have to ask ourselves if the suggested control strategy helps realize the specific objective or not. This assessment can be done qualitatively using +'s and –'s, as 'bullet point' scores, or color coding, or semi-quantitatively using numbers (Table 10.3).

In Step 1, examples of objectives, such as: minimize costs, minimize the rate of deterioration and maximize access to (the cultural values of) the collection and building were developed based on the mission statement. These are used to help choose between options by weighing them. In Step 9 several mitigation options are presented. These vary from doing nothing, relocating objects, object protection by microclimates, to changing the hygrothermal balance of the building by mobile systems or full, all-air climate control and combinations of these options.

Obviously choosing between control strategies on a macro level requires a different set of objectives, than choosing between similar control systems. Especially when larger control systems are considered, a set of new objectives, specifically related to the performance of HVAC-systems, might help choosing between systems. Examples of these HVAC system related objectives are:

- Stability and robustness of the climate control system
- Lifetime of components
- Reliability of the strategy
- Staff time required to operate and maintain the system
- Volume, size and amount of the climate control systems and ducts
- Effectiveness of the system to deliver heat and/or cooling
- Access to the climate control system
- Simplicity of operation
- Measuring technique

Since large climate control systems, such as all-air systems, consist of four functions:

- Central generation of warm, cold, dry, or moist air, whose main feature is a mechanical device;
- Distribution of: air, water (heating, cooling, consumption, draining). Main features are shafts and transport areas for pipes and ducts;
- Delivery by: radiators, post-conditioning cooling and heating units, air grilles and nozzles and fans;
- Measuring and regulating systems;

Objectives should be selected to consider all these components separately.

## 10.4 A Case Study

Amerongen Castle is a fully decorated historic house that represents the living history of a single family for more than 700 years. The moveable collection consists of an almost complete collection of art and artefacts from this one family until 1977, see Fig. 10.2. After which the house was sold to the Dutch State and was opened to the public under the care of a trust.

Floods in 1993 and 1995 had affected the moat surrounding the building and the electric wiring system, and caused biological infestations. This deterioration of the building created a high-risk situation for visitors. Moreover, the floods resulted in a significant change of the hygrothermal balance in the building, thus increasing the risk of an incorrect relative humidity to the highly valuable collection. This resulted in the castle being closed to the public in 2000.

The objectives to guide the restoration decisions were developed by an independent advisory committee. The most important notion was; 'that the aged authenticity, the patina of time, of the interior ensemble was regarded as one of the most important and rare aspects of the house' (van der Woude 2012).

The committee advised coherent conservation of the house and collection. Due to several expert meetings, organised over two years, a uniform advise could be formulated and values were shared between stakeholders (Kapelouzou 2012). The ensemble had 'grown old' together. It is not the individual artefacts or the building itself, but the ensemble in its original setting that makes Amerongen Castle so valuable.

The conservation focus became, respecting the existing fabric rather than renewing it. Therefore, the architectural finishing of the interior remained an important part of the historic house museum ensemble. All epochs of interior decoration and any architectural changes in the house made before 1977 were respected. The curator took on the task of safeguarding the completeness and authenticity of the interior ensemble during the planning and execution of the conservation of the building, ensuring that amongst all stakeholders, there was an understanding of minimal intervention.

**Fig. 10.2** The Grand Salon of Amerongen Castle

The objectives for this case study could be given as:

- Minimize the costs for implementation of a climate control strategy and energy consumption;
- Minimize the rate of deterioration to the interiors (building and moveable collection);
- Maximize access to (the cultural values of) the collection and building by providing a good experience to visitors by maintaining the patina of time;
- Minimize changes to the building.

After extensive monitoring of the indoor climate it was concluded that the indoor climate conditions created a significant mold risk due to a high relative humidity for long periods of time, and moderate risk of mechanical damage to the collection due to seasonal fluctuations of the relative humidity (Ritmeijer 2007; Huijbregts et al. 2014). To reduce these risks several options for climate control were considered. These varied from:

- No climate control actively controlling the temperature or relative humidity, but only reducing the infiltration through cracks and seams around window frames by restoring the windows;
- Conservation heating with mobile devices (already used for several years, see Fig. 10.3), combined with open doors and reducing the infiltration;

**Fig. 10.3** The Grand Salon of Amerongen Castle was used as temporary storage for the painting collection. The climate was locally controlled by conservation heating using an electric radiator

- A ‘slow’ floor-heating system under the tiled floors in the basement and the main (first) floor, so that the stone core of the building is used for ‘thermo storage’ during the summertime and natural mixing of warm air through the building using the open staircase and galleries, including reducing infiltration;
- Central heating radiators in the rooms for local heating of separate rooms combined with reducing infiltration;
- Installing an all-air HVAC system, using the ducts provided by the fire places and reducing the infiltration.

In Table 10.3 the options to reduce the risk of high relative humidity are weighed against the objectives. If an option does not help to achieve a specific objective a score of zero is given, if the option negatively affects the objective it scores ‘minus’ and positively if it helps achieve the objective. It should be noted that the costs are not real and should be seen as indicative.

Building a consequence table in which the consequences of different climate control options for different objectives are analyzed gives a rough indication of which options develop most objectives.

The ‘doing nothing’ option has low costs, will maintain the climate risk profile that has been unfavorable for many years, but will not affect the patina of time. The building fabrics will not be altered because no new systems will be installed.

**Table 10.3** The options are scored

| | Minimize costs (€) | | Minimize the rate of deterioration | | Maximize access to cultural values | Minimize intervention to the building |
|---|---|---|---|---|---|---|
| | Implementation | Energy | Building | Collection | Patina of time | Invasiveness |
| No control | 0 | 0 | −− | −− | ++ | ++ |
| Conservation heating with mobile devices | 10,000 | 10,000 | + | + | −−− | 0 |
| Conservation heating with floor heating | 50,000 | 5000 | + | + | ++ | − |
| Radiators | 20,000 | 5000 | −− | −− | −−− | − |
| All air HVAC | 500,000 | 50,000 | ++ | ++ | −− | −−− |

Conservation heating, see Fig. 10.3, will involve purchasing new devices. Control over the humidity will positively affect the indoor climate and the climate risks will be reduced. Placing radiators and humidifiers will greatly affect the experience value of the room, the patina of time will be disturbed by the visual presence of modern devices.

A floor-heating system under the tiled floors in the basement and the main (first) floor is costly. It is expected that the high relative humidity peaks can be reduced to an acceptable level and the patina of time can be fully maintained. Lifting floors and replacing is not without risk: the old uneven floor might be replaced slightly different. In the worst case a very smooth surface of old tiles will be the result.

Placing new installations, such as radiators underneath the windows, would entail (re)moving objects within the fully decorated interiors or affecting the overall image of the ensemble. The collection should retain its arrangement as of the mid twentieth century. The patina of time will be greatly affected by the radiators in the room. Local heat sources will generate gradients and will increase the climate risk.

An HVAC system which allows control over both temperature and relative humidity is expensive, will reduce deterioration of both the building and the collection. The patina of time will be negatively affected because space will be needed to place the system. Ducts, outlets and even draughts will reduce the historic sensation of the spaces.

Now that the consequences are scored, a problem arises. How can the financial costs be combined with the +'s and –'s of the other objectives? To solve this, so-called preference scales can be used. The relative (un)importance can be scored from 0 (least preferred) to 100 (most preferred). Within each column the lowest value scores 0 and the highest score is given 100, the other values in between are ranked or calculated according to those values (Table 10.4).

Additionally, it should be clear that not all objectives are always equally important. A weight or index can be added to each objective to indicate its relative importance. When several objectives have a different relative importance a list can be constructed. For each objective a numeric value, e.g. between 1 and 10, can be assigned that reflects its relative importance.

For Amerongen Castle the collection preservation, experience value and the patina of time were stated as most important and were thus arbitrarily given an index of 2. This index is multiplied by the relative score in the cells within that row (Table 10.5).

From this table it becomes readily clear that the 'slow' floor-heating system under the tiled floors in the basement and the main (first) floor achieves most of the objectives. It was decided to lift the historic tiles and install floor heating, see Fig. 10.4.

Obviously when the options are weighed and an index is given, the final ranking might change. It could be interesting to see how the ranking of the options changes with changing indexes for the importance of the objectives. For example, if collections preservation were less important and scored 0.5 instead of 2, the doing nothing option would then be the best strategy to achieve most objectives. This so-called sensitivity analysis would give some insight in to how preferences

**Table 10.4** Applying the preference scales

| | Total costs | Energy costs | Building preservation | Collection preservation | Patina of time | Invasiveness | Total score |
|---|---|---|---|---|---|---|---|
| No control | 100 | 100 | 0 | 0 | 100 | 100 | **400** |
| Conservation heating with mobile devices | 90 | 80 | 100 | 75 | 0 | 60 | **405** |
| Conservation heating with floor heating | 50 | 90 | 100 | 75 | 100 | 40 | **455** |
| Radiators | 80 | 90 | 0 | 0 | 0 | 40 | **210** |
| All air HVAC | 0 | 0 | 100 | 100 | 25 | 0 | **225** |

**Table 10.5** Applying a weight to the objectives

| | Total costs | Energy costs | Building preservation | Collection preservation | Patina of time | Invasiveness | Total score |
|---|---|---|---|---|---|---|---|
| Index | 1 | 1 | 1 | 2 | 2 | 2 | |
| No control | 100 | 100 | 0 | 0 | 200 | 200 | **600** |
| Conservation heating with mobile devices | 90 | 80 | 100 | 150 | 0 | 120 | **540** |
| Conservation heating with floor heating | 50 | 90 | 100 | 150 | 200 | 80 | **670** |
| Radiators | 80 | 90 | 0 | 0 | 0 | 80 | **250** |
| All air HVAC | 0 | 0 | 100 | 200 | 50 | 0 | **350** |

**Fig. 10.4** Installing floor heating in the central hall of Amerongen Castle (Photo: Jos Snoek)

for options depend on the relative importance of objectives. It also illustrates that a certain amount of uncertainty is inevitable and that structuring the decision using the consequence matrix helps accept this issue. Sometimes the objective is so important that if it is not achieved by a specific option it could be seen as a failure criterion and the option should not be considered further.

Ideally by looking at the advantages and disadvantages of selected options, and/or pairs of options, new options could be created that might be better than those originally considered. One could of course repeat the proposed process until the optimum option, which achieves most objectives, is developed.

Structuring a decision helps think it through thoroughly. Bringing alternatives, including 'doing nothing', to the surface enable all stakeholders to participate in the process. A clear structure allows an evaluation of the decision afterwards. This is especially relevant since most of the decisions made about controlling the indoor climate involve many stakeholders and sometimes even the broader public. Conflicting objectives will become transparent (see Fig. 10.5) and those involved can reflect on the choice to be made.

## 10.5 Conclusions

This chapter has outlined two possible methods, which can be used to evaluate the possible climate control strategies. These allow the options established in Chap. 9: Step 8, to be evaluated so that a mitigation strategy can be developed that helps achieving most objectives. There are many other methods that could be used for this analysis. However, these two methods are relatively simple and straight forward. They help making decisions transparently.

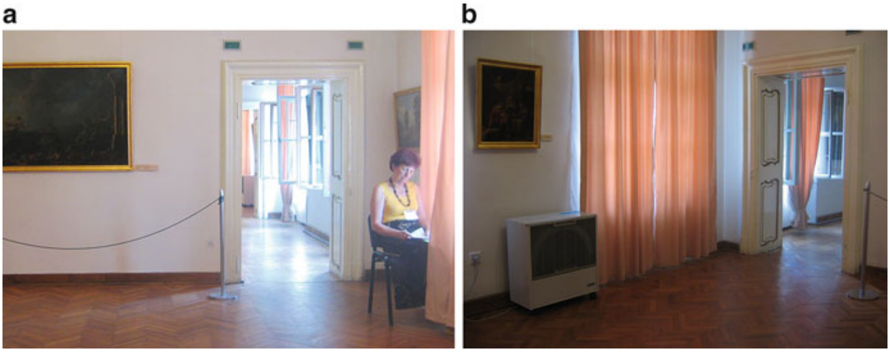

**Fig. 10.5** (**a**) What is more important, thermal comfort of staff or collection comfort? (**b**) Will the mobile device help control the indoor climate effectively when the windows are open?

We make decisions every day, often without giving it much thought. Yet, often certain forces influence the accuracy of these decisions. Rational decision making does not mean that the certainty of reaching a specific outcome increases. We have to accept that every decision that is made contains an uncertainty. Several issues play a role:

- Human psychology involves biases; the beliefs that we have, e.g. relative humidity fluctuations are always bad, guide our questions and the interpretation of the information that we gather. It can also be seen as a filter that influences our reality. We tend to dismiss what doesn't fit naturally.
- Due to the need to be certain, humans have a strong temptation to commit to a certain option too soon. Uncertainty is always there and should preferably be embraced and acknowledged, so that it helps 'think outside the box';
- The amount of information is potentially limitless and often the decision environment too complex. It is a real challenge to find the right amount of useful information to make the optimum decision.

So we have to accept that every decision has a degree of uncertainty, that each decision has a 'risk' associated with it. And that decisions made today will influence decisions that are going to be made tomorrow.

Structuring complex problems well and considering multiple criteria explicitly leads to more informed and better decisions. Going through the following steps helps you make the decision transparent, allowing stakeholders to participate and finding the optimum strategy to achieve your objectives. The overall decision making process using multi criteria analysis is:

1. Establish the decision context
2. Identify the objectives
3. Identify options
4. Assess the performance for each combination of options and objectives
5. Add weights for each of the objectives to reflect their relative importance
6. Calculate the relative scores for each option and evaluate the results

7. Perform a sensitivity analysis by changing the weights of each objective
8. Choose the climate control strategy that best helps develop the objectives.

The result of weighing the alternatives finally is a choice of the most optimum strategy that helps achieve most objectives.

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# Chapter 11
# Conclusions and Recommendations

## 11.1 Introduction

In the early days of museums, museum collection management was very different from what it is today. Objects of art, curiosities and archaeological finds were collected by royals, noble men, new merchants and banking families. These collections were symbols of social prestige. In the eighteenth century the Enlightenment and the growing taste for the exotic encouraged exploration of the exhibits in its broadest sense. Two of Europe's outstanding museums; the British Museum, in London, and the Louvre, in Paris opened in 1759 and 1793 respectively. When the predecessor of the Rijksmuseum in Amsterdam, the Nationale Kunstgalerij first opened its doors on 31 May 1800, it had about 200 paintings and historical objects on display. The collection was only visited by a very small fraction of citizens.

It was during the second half of the nineteenth century that museums began to see a roll in educating the masses. This influenced collecting and arranging artworks and the way displays were developed in their architectural setting. The prime objective of most museums was to show as many objects as possible and visitor numbers were limited.

In those days some public buildings were heated, but museums were generally unheated. An urgency to control the moisture content of the air was not yet felt. It must have been pretty cold in most museums in the Northern hemisphere. Due to these low temperatures, collections will have been exposed to relatively small seasonal relative humidity fluctuations. In those museums equipped with heating seasonal relative humidity fluctuations will have been larger and objects will have dried out in winter with subsequent damage. This risk experience resulted in climate specifications that became more stringent with every decade in the twentieth century. To maintain a museum climate within a narrow bandwidth, required large climate control systems to produce air of precise quality. The specifications for the relative humidity of $50 \pm 5\,\%$, $48{-}53\,\%$ or even $51 \pm 1.5\,\%$ were provided by governmental institutes and climate engineers.

B. Ankersmit, M.H.L. Stappers, *Managing Indoor Climate Risks in Museums*,
Cultural Heritage Science, DOI 10.1007/978-3-319-34241-2_11

Today most heritage institutions will have different objectives. The focus is to provide visitors with stories of objects and people and to give an (emotional) experience in a comfortable and welcoming atmosphere. Museums are required to be financially more self-sustainable. Costs are to be reduced and a focus will be to raise income. This results in exhibitions in non-traditional spaces and non-traditional museum events in exhibit spaces. There is considerable pressure to reduce operating costs but still provide a comfortable visit to as many visitors as can possibly be handled, see Fig. 11.1. The ambition to increase collection mobility and by doing so increasing the amount of people enjoying cultural values, is a strong driving force for the discussion on loan demands. This debate takes place between a group of museum directors, called the Bizot group, of internationally leading museums.

Also the international conservation community produced the so-called '*Environmental Guidelines IIC and ICOM-CC Declaration*'. In which it is stated that:

- The issue of museum sustainability is much broader than the discussion on environmental standards, and needs to be a key underlying criterion of future principles.
- Museums and collecting institutions should seek to reduce their carbon footprint and environmental impact to mitigate climate change, by reducing their energy use and examining alternative renewable energy sources.
- Care of collections should be achieved in a way that does not assume air conditioning (HVAC). Passive methods, simple technology that is easy to maintain, air circulation and lower energy solutions should be considered.
- Risk management should be embedded in museum management processes.

On the environmental aspects the declaration states:

- It is acknowledged that the issue of collection and material environmental requirements is complex, and conservators/conservation scientists should actively seek to explain and unpack these complexities.

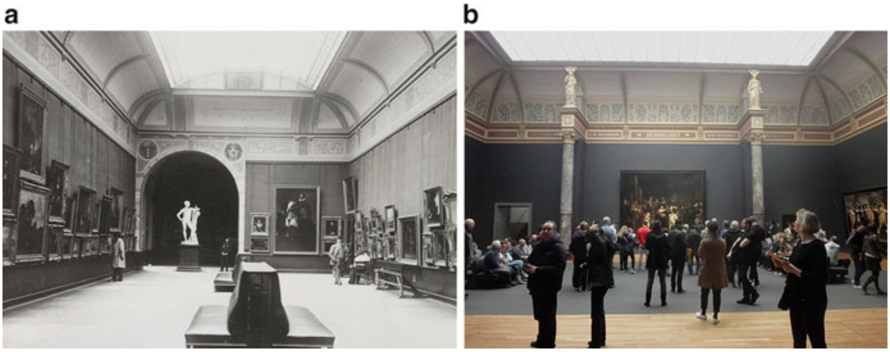


**Fig. 11.1** The permanent exhibition in the Haarlemzaal of the Rijksmuseum in Amsterdam around 1888 (**a**) and the well visited Night watch Gallery in 2015 (**b**)

- Guidelines for environmental conditions for permanent display and storage should be achievable for the local climate.

Especially the unraveling of the complexity of the decision making encouraged us to write this publication. We hope that with it, we can help those responsible for the museum climate, to make well informed decisions to optimize their climate in a sustainable way. To unravel the arguments to reduce indoor climate risks is a complex business, the stakes are high, the information is complex, it is time consuming and often very expensive. Developing options to reduce indoor climate risks is not a daily task for many. Probably within a heritage institute large refurbishments take place once in a lifetime. So museum staff with broad experience in going through the motions of finding the optimum strategy to reduce indoor climate risks to an acceptable level are very limited in number. Therefore this book attempts to give an overview of the knowledge that can be used to make informed decisions concerning the museum indoor climate. Nine steps are proposed to structure the decision making process, see Fig. 11.2.

In Chap. 9, Step 8 climate control strategies are proposed, which must then be validated according to the principles and conditions established in Steps 1–5 and contained in Step 7. It is indeed a time-consuming process that involves gathering information by talking to relevant stakeholders, looking at the collection and the building, measuring the climate, analyzing the building physics and if there is an HVAC present, the HVAC performance and most important, understanding the decision to be made. It is believed that this investment in time and often also money, will result in savings afterwards. But more importantly, it is precisely this investment in time and knowledge that will be the main measure taken to reduce the risk of an incorrect climate and an incorrect climate control! Excessive time pressure during the process is the greatest danger of a undesirable outcome for every climate control project. By going through each step, a comprehensive identification and analysis will lead to an enormous increase of knowledge within the organization about the value of the building, its fixtures and the collection, about the possibilities offered by the building, the potential risks to the building and the movable collection, the options to mitigate the indoor climate risks and the arguments that are valid to guide the decision.

In larger projects, such as refurbishing large museums, building a new storage facility etc., the proposed decision making process cannot be seen separately from the overall building process. Architects and their sub-contractors typically follow a step process: from a preparation phase to a construction, and use and after care phase. In between there are several moments where the concept design is formalized into a technical and specialist design, which cannot be adapted easily afterwards. If the nine steps of managing the indoor climate risks are not properly incorporated into the building plan, the outcome might not be ideal. It is essential that enough time is allocated to allow the development of an optimal climate strategy and that this is done in the preparation and concept phase of the building project.

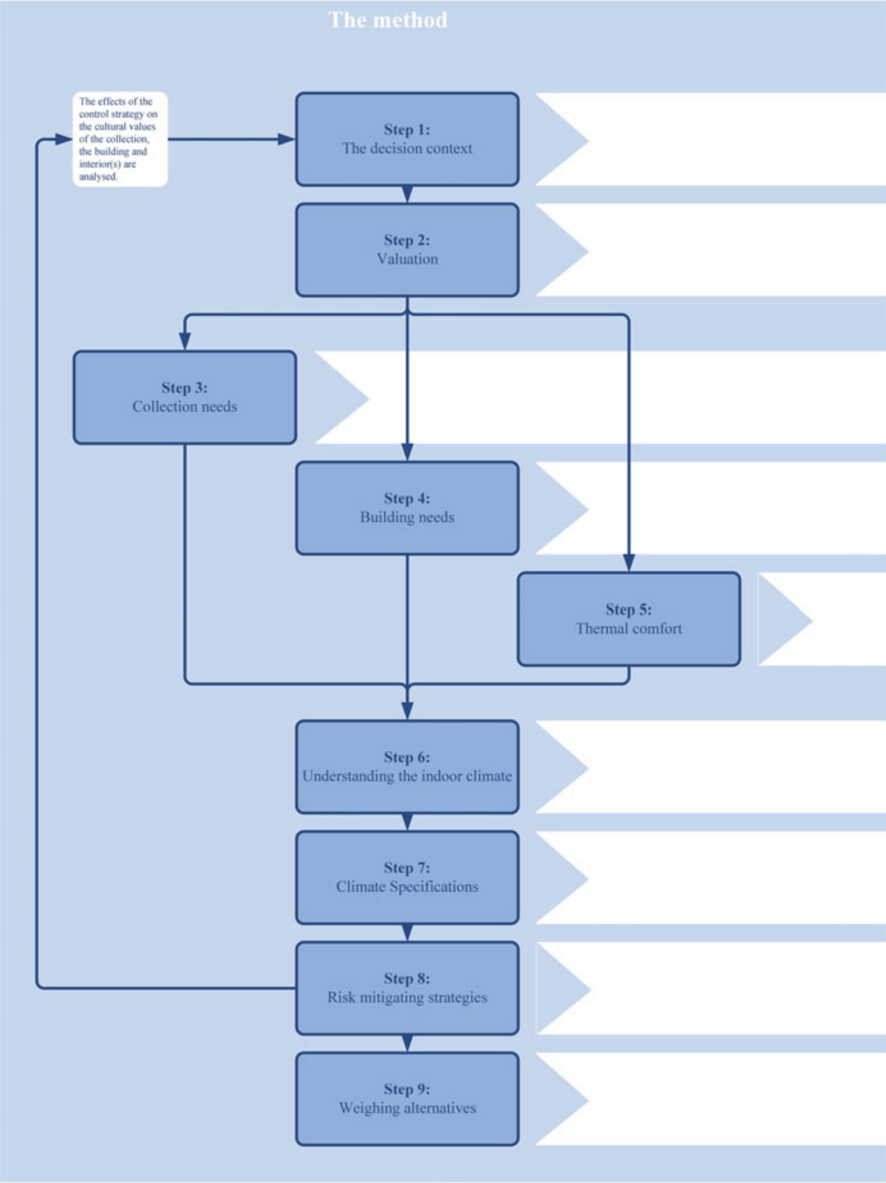
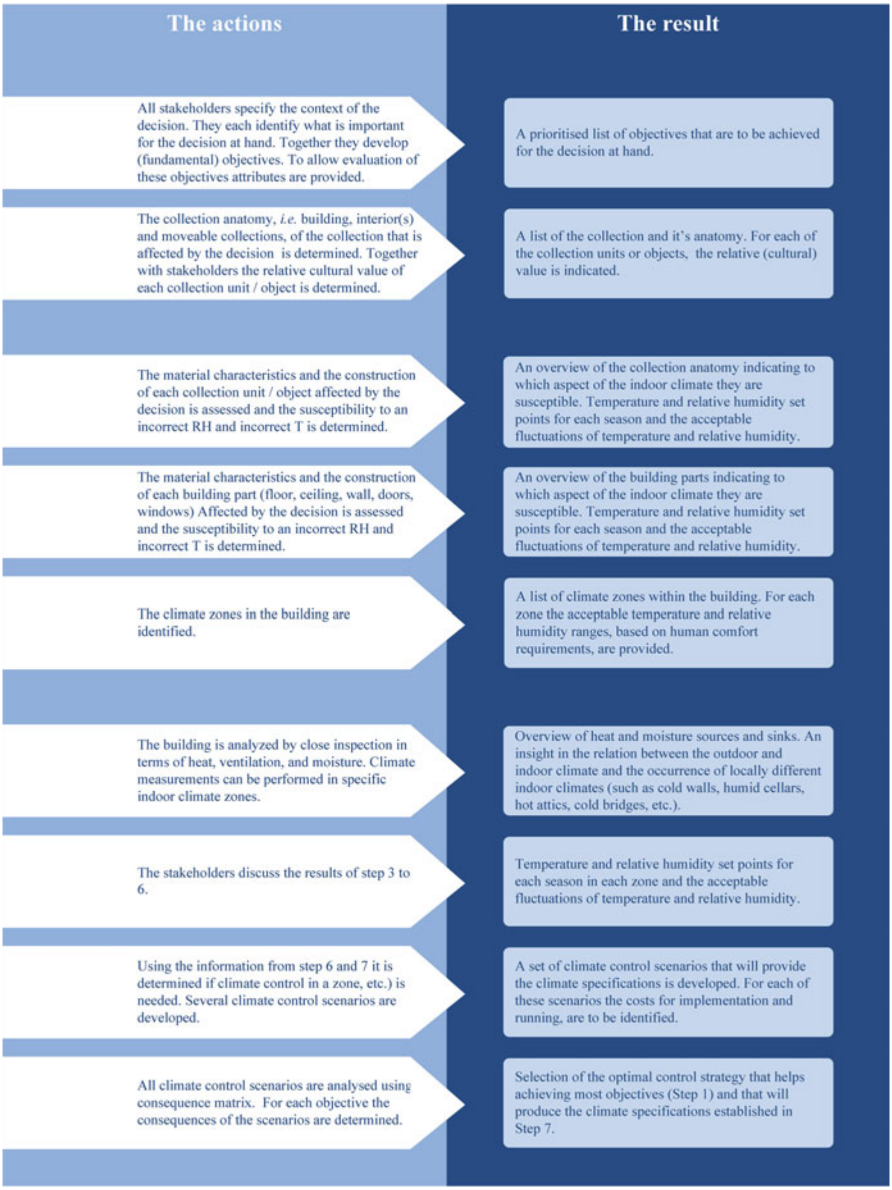


**Fig. 11.2** The nine steps of the decision making process to manage indoor climate risks in heritage institutes



| The actions | The result |
|---|---|
| All stakeholders specify the context of the decision. They each identify what is important for the decision at hand. Together they develop (fundamental) objectives. To allow evaluation of these objectives attributes are provided. | A prioritised list of objectives that are to be achieved for the decision at hand. |
| The collection anatomy, *i.e.* building, interior(s) and moveable collections, of the collection that is affected by the decision is determined. Together with stakeholders the relative cultural value of each collection unit / object is determined. | A list of the collection and it's anatomy. For each of the collection units or objects, the relative (cultural) value is indicated. |
| The material characteristics and the construction of each collection unit / object affected by the decision is assessed and the susceptibility to an incorrect RH and incorrect T is determined. | An overview of the collection anatomy indicating to which aspect of the indoor climate they are susceptible. Temperature and relative humidity set points for each season and the acceptable fluctuations of temperature and relative humidity. |
| The material characteristics and the construction of each building part (floor, ceiling, wall, doors, windows) Affected by the decision is assessed and the susceptibility to an incorrect RH and incorrect T is determined. | An overview of the building parts indicating to which aspect of the indoor climate they are susceptible. Temperature and relative humidity set points for each season and the acceptable fluctuations of temperature and relative humidity. |
| The climate zones in the building are identified. | A list of climate zones within the building. For each zone the acceptable temperature and relative humidity ranges, based on human comfort requirements, are provided. |
| The building is analyzed by close inspection in terms of heat, ventilation, and moisture. Climate measurements can be performed in specific indoor climate zones. | Overview of heat and moisture sources and sinks. An insight in the relation between the outdoor and indoor climate and the occurrence of locally different indoor climates (such as cold walls, humid cellars, hot attics, cold bridges, etc.). |
| The stakeholders discuss the results of step 3 to 6. | Temperature and relative humidity set points for each season in each zone and the acceptable fluctuations of temperature and relative humidity. |
| Using the information from step 6 and 7 it is determined if climate control in a zone, etc.) is needed. Several climate control scenarios are developed. | A set of climate control scenarios that will provide the climate specifications is developed. For each of these scenarios the costs for implementation and running, are to be identified. |
| All climate control scenarios are analysed using consequence matrix. For each objective the consequences of the scenarios are determined. | Selection of the optimal control strategy that helps achieving most objectives (Step 1) and that will produce the climate specifications established in Step 7. |

**Fig. 11.2** (continued)

## 11.2 Conclusions

We must realize that different people have different ideas about what needs to be achieved. Finding common ground between stakeholders, i.e. interdisciplinary team of professionals (architect, installation engineer, facility manager, curator, architectural historian) about what is important and evaluate the challenges is the basis to develop any climate optimization project further. Defining the context, the process and the boundary conditions for the project manager is key. Considering all the arguments and finding an optimum indoor climate that does justice to all, or most of the ambitions, of all or most stakeholders, is a challenge. Every situation is unique and will require a specific way of managing the project. Obviously, small decisions with relatively small financial impacts involving only a small part of the collection (value) can generally be agreed more easily than projects that involve major building work, have an impact on most of the collection (value) and require a large budget. In this step it is crucial to 'think outside the box' and develop options that can be evaluated and really allow realization of your ambitions.

One of the objectives that will be developed in the project team will be the preservation of cultural values. Therefore, it is advisable to define the cultural values of the heritage assets on which the decision has an impact. The process of valuation can start by defining the collection anatomy, compiling all relevant information and then to engage in discussions with the stakeholders. A valuation report can be jointly produced, which would serve as a basis throughout the decision making process. In the valuation document, an attempt should be made to define the distribution of the different values over the collection units and/or the building. Obviously, not all decisions related to managing indoor climate risks require such an extensive analysis of the individual significance of the heritage assets involved, a rough indication of value distribution over collection units can also be very useful. It should be noted however that in many cases the climate risks are only managed by making large decisions every 30–50 years when a building is extensively adapted and made ready for the next generation. Since large amounts of money are involved and much cultural value can potentially be lost, it seems logical to make these value based decisions assessing the significance of all the assets affected.

The priorities of the institution, values of the building and collection, as well as their needs and those of users, will shape the final specifications and requirements of any climate optimization. Therefore the climatic needs for the collection, the building and the people will have to be determined.

The most general conclusion to be drawn from the information presented in Chap. 4, Step 3 is that many objects have survived remarkably well in conditions that were far from the classical 'ideal', which shows us that strict climate specifications for objects is not required per se. It is essential to realize that a single universally safe relative humidity value does not exist for the preservation of our valuable heritage. Collections in museums are composed of different sub-collections, which are in turn are composed of a variety of objects. The objects are made of a multiplicity of materials, which are combined in a variety of constructions. It is often true that different objects react differently under the same environmental conditions, which causes them to experience different climate risks that could result in damage. It is therefore essential to identify the most susceptible objects in the collection. Evidently, in this context, the term ‘objects’ can also be used to refer to the building and its fixtures. If the susceptibility of objects is related to their (cultural) value, then priorities can be established. These priorities will reflect the fact that exposure of the most valuable and susceptible objects, with potentially a high loss of value, will primarily deserve our attention and budgets. Risks can be better accepted for less sensitive and/or less valuable objects. Objects with the following characteristics should therefore be identified in the collection:

- Susceptible objects that consequently could be under a high risk of damage due to an incorrect indoor climate;
- Objects that will experience a large loss of value when an incorrect indoor climate changes the object.

Since the climate risk to the moveable collection should be well understood for any decision to be made on collection care by climate control, some general notions should be clear. Based on the available literature, the following can be stated about collection needs in general:

- The risk of chemical decay can be reduced by lowering the temperature. A rule of thumb is that lower the temperature by 5 °C (9 °F) will double the lifetime.
- A relative humidity higher than 75 % for prolonged periods of time will significantly increase the risk of biological decay. The risks of corrosion of metals and sick glass, and the thriving and increased activity of a number of damaging insect species will also increase.
- A relative humidity fluctuation of 10 % (daily or yearly) around a relative humidity value of 45 %, 50 % or 55 % is a low risk of mechanical damage to almost all hygroscopic objects.
- A relative humidity fluctuation of 15 % around an average value of 45 %, 50 % or 55 % constitutes a low risk for most, but not all hygroscopic objects.
- A relative humidity fluctuation of 20 % around an average value of 45 %, 50 % or 55 % is dangerous for some composite objects.
- A relative humidity fluctuation of 40 % around an average value of 45 %, 50 % or 55 % is destructive for most objects made of organic material.

It is clear that the highest risks to (historic) buildings is not an incorrect indoor climate. Although heating by direct sunlight can cause cracks may be formed from the outside to the inside due to subsidence in massive masonry or concrete buildings. Through these cracks rainwater can easily penetrate into the building. Liquid water will flow from the outside to the inside, carrying dissolved salts. When this water evaporates, crystals are formed. Maintenance of the building fabric is the key mitigating strategy here. Structural stability, keeping the building wind- and watertight and proper rainwater management is of upmost importance. If moisture can accumulate in the building fabric the risk of rot and mold are significant. At very low temperatures the risk of freezing and condensation increases.

People are most susceptible to temperature. Providing visitor comfort requires a control of the temperature. Controlling the temperature for thermal comfort will influence the risks of chemical deterioration, biological decay and mechanical damage. Heating the indoor air will increase the risk of chemical decay of chemically unstable materials. In climate zones with (very) low outdoor temperatures the relative humidity will drop and the risk of mechanical damage will increase. To reduce the risk related to low relative humidities, the indoor air could be humidified, which can increase the risk of biological decay, especially on cold surfaces. So, especially in cold climates it seems logical to accept a slightly cooler indoor climate to control these risks. Reducing thermal comfort will increase collection comfort and will reduce energy consumption. If the indoor climate is also humidified in winter to control relative humidity, lower indoor temperatures will also reduce the required capacity for humidification and the risk of mold due to a lower condensation temperature.

In tropical climates however, maintaining a relatively low relative humidity and reduce indoor temperatures by cooling will reduce chemical and biological risks to the collection but may increase the risk of mechanical damage. Many objects in the collection will have been exposed for a very long time to much higher relative humidity levels. Reducing the relative humidity will also require substantial investments for climate control systems and the energy needed to run the machinery.

In the past decades the tendency in the heritage field was to gain control over the indoor climate primarily by mechanical equipment. Buildings were adapted to this new hygrothermal balance by making them more airtight and sometimes by applying insulation and water vapor barriers. More and more the characteristics of the materials used are chosen based on their ability to positively influence the indoor climate and thereby reduce the capacity of mechanical systems. To make the right choices it is important to know what the current indoor climate is, and how this is influenced by the building fabric and construction. The next seven steps might serve as a guide to start understanding the indoor climate:

- Determine the orientation of the building and solar gains, wind speeds and wind directions for the building location. These parameters can be measured independently or obtained from a local weather station;
- Inspect the building on the outside and inside for possible defects. Several visually observable phenomena can help identify problems in the building envelope: salt efflorescence, algae growth, wet areas, cracks, seams, surface or interstitial condensation, mold growth etc.;
- Take measurements of the outdoor and indoor climate. The temperature and relative humidity over a period of time give insight in the possible climate risks for the building, interior or collection as presented in Chaps. 4 and 5. Comparison with the outdoor climate gives insight in to how the building affects the indoor climate. The outdoor climate can be measured independently or obtained

from a local weather station. The indoor climate also can be measured independently or can be outsourced to a commercial company;

- Make an assessment of the hygrothermal properties of the building envelope to understand why there is a difference between the outdoor and indoor climate. Gather information on the building envelope regarding: the type of building materials, dimensions of transparent and non-transparent surfaces, layers of building construction from outside to inside, connections between different building parts, etc.;
- Make an assessment of the air exchange rate;
- Make an assessment of internal heat and moisture sources and sinks, considering both dynamic and static sources and sinks. Estimate how each zone is influenced by these sources, or sinks, for how long and at which interval;
- Make an analysis of the gathered data. Keep in mind when looking at climate data whether or not these form an actual threat to the building, interior, or collection. Establish whether any indoor climate parameter is a threat: temperature, relative humidity, or their fluctuations. Be precise. Then try to understand why this parameter differs from the optimal.

Once the indoor climate is understood in more detail, the next step is to make small, or large changes within the context of the (historic) building. These may include changes in building management, adaptations of mechanical equipment, or alterations to the building fabric.

The information gathered in earlier steps now needs to be combined to develop the climate specifications for the zones in the museum. The priorities of the institution, values of the building and collection as well as their needs and those of users will shape the final specifications and requirements. Combining technical information about building physics, material science and human behavior with design and cultural experiences requires a process in which very different stakeholders are to be heard. An independent moderator can lead the group of stakeholders through a process in which different types of information is shared, discussed and evaluated, leading finally to a set of relative humidity and temperature set points and acceptable fluctuations that can subsequently be used to develop the optimal mitigation strategy.

Mitigating climate risks to collections and the building or optimizing human comfort generally includes improving the physical properties of the building and/or implementing a system to influence the temperature and/or relative humidity. Several strategies should be developed. The following steps to develop climate control strategies are suggested:

- Take advantage of the physical properties and architectural features of the building, as well as of other existing possibilities in the current situation (e.g. sun-blinds and natural ventilation), to regulate the indoor climate;
- Investigate the possibilities of implementing complementary structural and physical measures to the building to reduce the impact of the outdoor climate on the indoor climate;

- Consider a ‘box-inside-a-box’ construction;
- Consider placing objects inside showcases or microclimate enclosures. The climate inside the showcase or enclosure can be controlled passively or actively;
- Keep in mind the building’s use, and the impact of user dynamics/behavior on the indoor climate. Consider, for instance, hanging wet coats in a separate area, not allowing large groups of people to remain inside small collection spaces for long periods of time, and avoid or limit ventilation with outside air during heat waves (or very cold days). In such situations, consideration should be given to adjusting the use of the building and for example, the number of visitors;
- Finally, introduce climate control system (if necessary) as an addition to the preceding points. The type and size of the installation depends on each specific situation. A feasibility study provides an indication of the (most appropriate) installation concept and associated costs. Actively changing the hygrothermal properties of the indoor air is done by air condition systems with the basic functions of heating, cooling, humidification, dehumidification, ventilation, and air purification (filtering). In smaller heritage institutes only specific functionalities are used by mobile devices, such as humidifiers or air conditioners to cool. Large heritage institutes with large visitor numbers often choose to control the indoor climate using full climate control. This allows increasing precision in controlling the relative humidity and temperature and control over air ventilation, filtering, and air distribution of the entire space. The quality of control depends on the layout of the zones within the building and the HVAC systems. The long term performance of the systems depends on management and maintenance.

Introducing a climate control system and making structural and technical modifications in a building will never fully eliminate climate-related risks to the collection. Firstly, it may be expected that the installation will reduce short fluctuations to a minimum; however, given the physical aspects of the building, seasonal variations often cannot be completely prevented. Secondly the risk of short and severe climate fluctuations increases when the indoor climate is entirely dependent on the installation. In case of equipment failure, just like when the outdoor climate is extremely hot or cold, the indoor climate can experience sudden and extreme changes, depending on the outdoor conditions.

When deciding on the implementation of climate control it seems that the need for cold storage in many collections in the northern hemisphere is subordinated to the desire for an ideal uniform and comfortable indoor climate. There is often a high priority and commitment to keep the risk of mechanical damage as small as possible by reducing the short and seasonal relative humidity fluctuations to a minimum. Generally decision makers prefer the best available technology over a balanced use of the building and its (minimal) systems. It should be made more clear that the risk of mechanical damage due to relative humidity fluctuations, is smaller when one has more experience with climate-related risks in the past. So the smaller the risks of future mechanical damage will be!

To evaluate the alternatives to optimise the indoor climate can be done by analysing which option helps achieving most objectives. A simplified multi-criteria decision analysis allows criteria to be weighed with different units. Building a consequence matrix, in which the consequences of different climate control options for different objectives are analyzed, helps to make a choice. This approach gives an indication of which options help to develop the most objectives. Rational decision making does not necessarily mean that the certainty of the outcome increases. We have to accept that every decision contains an uncertainty. But structuring complex problems well and considering multiple criteria explicitly leads to more informed and better decisions. Going through the following steps helps you make the decision transparent, allowing stakeholders to participate and finding the optimum strategy to achieve your objectives. The overall decision making process using multi criteria analysis is:

- Establish the decision context
- Identify the options
- Identify objectives
- Assess the performance for each combination of options and objectives
- Add weights for each of the objectives to reflect their relative importance
- Calculate the relative scores for each option and evaluate the results
- Perform a sensitivity analysis by changing the weights of each objective
- Choose the climate control strategy that best helps develop the objectives.

## 11.3 Recommendations

In order to estimate the risks to the collection, knowledge about the conditions around the objects should be available. This means that the climate needs to be (locally) measured and understood. Next to measuring with relative humidity and temperature data loggers, it is possible to obtain useful information about local temperature differences by thermal imaging with an infrared camera. These measurements are only relevant when the data is subsequently used for the decision making. This means that collecting data is not a goal in itself, but a means to an end! Therefore it seems logical to develop a research question that allows proper placing of loggers and analysis of the collected data.

The measures that can be implemented differ from building to building, from collection to collection and on the availability of finances, not only to implement a control strategy but also to maintain it (total cost of ownership)! It is advisable to initially look for small interventions or modifications that will not significantly affect the way the collection is used and/or the room is experienced. In practice, this means that one should consider too:

- Do nothing and accept the risk;
- Relocate susceptible objects to areas (zones) that naturally have a better climate;

- To organize exhibitions with susceptible artefacts in less critical seasons than summer when it's hot and humid or winter when it's cold and dry;
- To relocate very susceptible objects to a stable storage and replace them for less susceptible or less valuable objects that allow telling the same story.

The aim should be to achieve sustainable solutions that limit as much as possible the consumption of energy and other resources. Climate control with minimal energy consumption should be a fundamental goal in every new building project. Energy efficient museum buildings become possible, with the development of a comprehensive design approach of architects, engineers and experts. New knowledge about passive and active architectural and technical ways to influence the indoor climate have become available. Considering passive control by thermal capacity, shading devices and buffering or active means like smart ventilation can significantly reduce energy consumption. The development of ultralow storage facilities in Denmark and currently also in the Netherlands deserve to be looked at as models to see the theory put into practice.

Adaptation of temperature set points to outside temperatures instead of a constant temperature should be considered. Especially in regions with low winter outdoor temperatures this could generate significant energy savings. Since human comfort is not required outside opening hours, temperatures could be allowed to drop at night (maintaining a certain control over the relative humidity). The amount of fresh air, i.e. ventilation, is never required by the collection, and the amount of recirculated air should be maximized.

Changing the hygrothermal balance in a building is not without risk. Some risks are reduced with the introduction of a climate control system, but also new risks are created. If the indoor climate is very different from the outside climate, the climate system plays an important role. The risk of a short and severe climate fluctuation increases as the risk of system malfunction increases. Equipment malfunction is more likely to occur precisely when the outdoor conditions are more extreme: too cold or too hot. In the event of failure of the climate control installation, the indoor climate will change abruptly and severely. Objects with response times of the same order of the downtime, typically 24 h, and objects with a vulnerable surface such as polychromed wooden sculptures in poor condition, are at a significant risk of damage. It is advisable to take measures such as proper procedures for maintenance, collection preservation or in some cases temporary evacuation of susceptible objects.

The end result of completing the nine steps is a well-founded choice for a climate control strategy based on a set of requirements for the indoor climate in the relevant spaces, including boundary conditions concerning the (cultural) value of the (historic) building, the collection, their use and financial and knowledge constraints. Such a document is the starting point for the design process. Sometimes the object is of such an importance and complexity that only drastic measures to control the indoor and sometimes even the outdoor climate can be made, an example is given in Fig. 11.3.

**Fig. 11.3** The wooden house of the second World War Nazi camp commander in Westerbork the Netherlands. The original house and its contents are too fragile to be exposed to the harsh outdoor conditions. A display case was designed with a natural ventilation to maintain temperatures and relative humidities that will help preserve the building for future generations. The house can be visited on invitation only, while inside the display case on the back of the house special events, such as small classical music concerts, are to be organized

## 11.4 Quick Reference Guide

This quick reference guide gives a brief overview of the most important criteria, based on which decisions about the indoor climate can be made. In the foregoing, these criteria are further developed in successive steps. Hereby it is possible to make well-planned choices, and to explicitly weigh different criteria and arguments against each other.

Step 1. A balanced decision is developed by exploring the decision context and the decision process (see Chap. 2). The goals of the heritage institute and the stakeholders involved are expressed, structured and if necessary prioritized. Attributes can be assigned to be able to analyze the success or failure of the option finally implemented.

Step 2. The process starts by making the significance of the building and the movable collection explicit (see Chap. 3). The final decision concerning a possible modification of the indoor climate starts with an understanding of the significance and future use of the building and the collection. This understanding can be obtained, among other approaches, by formulating a statement of significance based on the mission of the museum or institution, and on the policies and interests of other direct stakeholders. Significance encompasses all historic, aesthetic, scientific, and social values that an object (collection or building) has for past, present, and future generations. It also refers to all elements that contribute to the significance of the object, such as context, history, and use.

Step 3. The collection needs are defined. In order to carry out this (risk) analysis, the sensitivity of the materials that constitute the collection and the building must be known (see Chap. 4). For historic ensembles, this means the analysis of risks for the whole of immovable (fixed) and movable objects. The collection can be divided into sensitivity categories containing materials/objects that have different environmental needs. Subsequently, the climate-related risks that must be reduced are determined for each category. Some evident criteria to be used include (in no particular order):

(a) The higher the temperature (and to a lesser extent the relative humidity), the faster the chemical degradation (hydrolysis and corrosion) and therefore the shorter the expected usability (lifetime) of a number of materials such as wallpaper, paper, photographs, paintings.
(b) At relative humidities above 65 % there is a high risk of biodeterioration (mold growth) of organic materials and corrosion of metals. In the proximity of cold surfaces, however, the relative humidity will be higher thus resulting in a high risk of biological activity. Think about the accelerated rotting of wooden window frames and/or beam heads.
(c) For materials containing water of crystallization (such as some minerals) or organic materials, the relative humidity should not fall below their critical lower limits (irreversible drying) or exceed their critical upper limits (gelatinization, deliquescence, expansion, and transport). Concerning transport phenomena, one can think of salt efflorescence in walls and floors.
(d) Relative humidity fluctuations should remain within the acceptable/safe ranges for the different sensitivity classes, or:
(e) Relative humidity fluctuations around the annual average should remain within the proofed fluctuation range.
(f) Large relative humidity fluctuations whose duration is longer than the response time should be avoided.
(g) Avoid condensation onto cold surfaces. This is an indication of climate-related risks elsewhere in the building envelope.
(h) The desire for (inter)national loans requires that conditions are created around objects according to loan agreement specifications. Internationally, these conditions are typically a relative humidity of 50 % with a maximum allowable fluctuation of 5 % (per hour, per day, or in general terms between 45 % and 55 %), and a temperature between 18 and 22 °C. Such an environment is also referred to as an 'AA climate'
(i) In situations where objects are regularly moved between storage and exhibition areas, it is sensible to adjust the respective temperature and relative humidity setpoints not too far apart from each other. In other words: $RH_{storage} \approx RH_{exhibition}$ and $T_{storage} \approx T_{exhibition}$.

Step 4. Those parts of the building that are considered valuable and susceptible to certain climate conditions are identified (see Chap. 5). The building needs are defined. The building materials can be divided into sensitivity categories containing materials/objects that have different environmental needs. Subsequently, the climate-related risks that must be reduced are determined for each category.

Step 5. The climatic requirements for the human occupants are defined for each climate zone (see Chap. 6).

Step 6. A building provides an (natural) environment with a certain indoor climate. Understanding the building physics allows an assessment of the building envelope properties that can be optimized to reduce risks to the moveable and immoveable collection (see Chap. 7).

Step 7. In preparing a balanced decision, the climate needs for collection, building and humans are combined with other boundary conditions and objectives to be used as a starting point to develop options to mitigate climate risks (see Chap. 8).

Step 8. Within the museum objectives and the value framework established in Step 1, the options to improve the indoor climate are considered and selected (see Chap. 9). A strategy for the efficient and sustainable implementation of climate strategy is then developed. Determine if the risks are acceptable or if they should be reduced. If adjusting the indoor climate is desirable, two possible strategies can be considered:

(a) Climate control locally around individual objects, or
(b) Climate control around the entire collection.

In the first case, environmental factors are locally modified while the room conditions remain unchanged. In the second, interventions are made to adjust the climate conditions at the room/building level. Define which modifications are feasible, taking into account the entire scale of possibilities: from microclimates to building physics. Also determine to what extent the significance of the collection will be affected by the implementation of the measures being contemplated. The statement of significance plays an essential role here.

Step 9. The decision about the implementation of a given strategy can be finalized with help of a cost benefit analysis (or a multi criteria analysis), in which value changes and preservation are weighed against the costs of implementation and maintenance in order to achieve the objectives developed in Step 1 (see Chap. 10). In this context, costs should not be interpreted as monetary value only, but as everything that is handed over or lost in terms of 'value'.

It is strongly recommended to meet with all internal and external stakeholders early in the process to discuss the different steps to be taken. Once the schedule of requirements (SoR) is concluded, only limited or often no alteration can be made. Although it may appear at first a time-consuming effort, this can ultimately speed up the entire project, providing a much higher chance of reaching the optimal solution for the indoor climate problem.

# Appendices

## Appendix 1: Glossary and Explanatory Notes

**Absolute humidity (specific humidity)** is the amount of moisture present in a given air volume. It is measured in units of grams of water vapor per kilogram of dry air (g/kg) or grams of water vapor per cubic meter of air (g/$m^3$).

**Adaptive thermal comfort** is a theory that suggests that people have a connection to the outdoor climate, which allows them to adapt to (and even prefer) a wider range of thermal conditions.

**Adiabatic humidifiers** introduce moisture to the air without adding thermal energy i.e. without raising the temperature. Standalone adiabatic humidifiers that operate on evaporative humidification, the air is blown through a wet filter by a ventilator. When air passes through the filter its humidity increases. This humidification process prevents the introduction of water droplets in the room. The possible formation of mineral deposits is also decreased. This type of humidifier is the most used in museums. Central adiabatic humidifiers that operate with ultrasonic humidification, ultrasound waves are produced with help of an oscillator. These waves generate a water mist made of very small droplets, of the order of 1–5 μm. Demineralised water should preferably be used for the operation of such systems, to prevent the deposition of salts.

**Air exchange rate** (AER) defines the amount of times a given volume is exchanged per time unit (day or hour) by infiltration, exfiltration and ventilation.

**Anisotropy** describes the effect that properties of a material, such as wood, are directionally dependent.

**All-air system** is a type of air conditioning system that regulates the indoor climate conditions such as temperature and relative humidity exclusively by introducing pre-conditioned air in the zone.

**Box-inside-a-box construction** is a closed volume within a space. A typical example is a closed and insulated storage area on the attic.

B. Ankersmit, M.H.L. Stappers, *Managing Indoor Climate Risks in Museums*,
Cultural Heritage Science, DOI 10.1007/978-3-319-34241-2

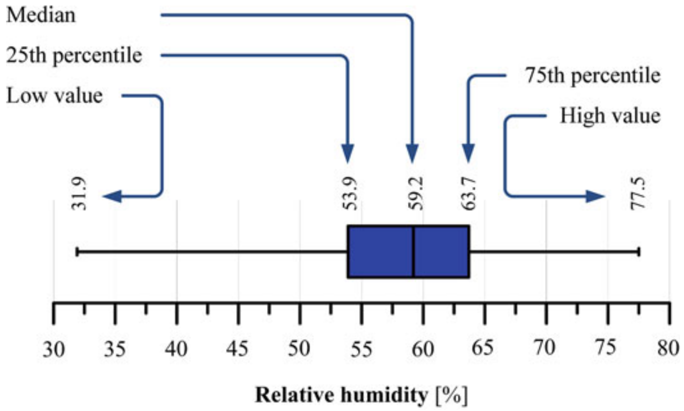


**Fig. A1.1** Example of a box-and-whisker-plot of a series of measured relative humidity data

**Box-and-whisker plot** is a graphic representation of five values from a numeric data set (see Fig. A1.1): the smallest observation or minimum (lowest point), the first quartile (or 25th percentile; represented by the lower side of the box), the median (or 50th percentile; represented by the line inside the box), the third quartile (or 75th percentile; represented by the upper side of the box), and the largest observation or maximum (highest point).

**Capillary sorption** is the action of surface tension forces which draws water into capillaries.

**Chemical stability** is the term used to express the extent to which materials are susceptible to undergo chemical changes under the influence of their environment. Examples of these chemical changes include the depolymerisation of cellulose due to acid catalysed hydrolysis, oxidation and cross-linking of oil paint, fading of dyes and oxidation of early (synthetic) polymers such as cellulose-acetate and –nitrate and many other chemical reactions taking place in (cultural) materials.

**Conduction** is the transfer of energy within a material due to a temperature difference.

**Convection** is the transfer of heat or moisture by air flow due difference in air pressure.

**Creep** is the deformation under permanent stress. It can occur as a result of long-term exposure to (high levels of) stress that are still below the yield strength of the material.

**Crosslinking** is the process through which covalent or ionic bonds are formed between two or more polymer chains. A typical result of this chemical bonding is that materials become stiffer and more brittle.

**Deliquescence point** is the relative humidity value above which a (salt) crystal dissolves and a liquid solution is formed by absorbing water from the atmosphere. Below this relative humidity value this (salt) crystal is in its solid state.

**Diffusion** is the process in which molecules move from a highly concentrated area to a place where there are fewer molecules, and thus a lower concentration.

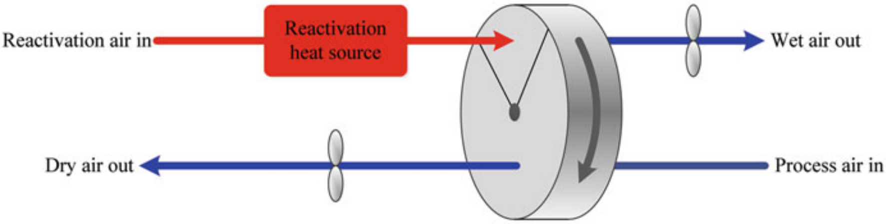


Fig. A1.2 Schematic representation of a basic dry-desiccant dehumidifier

Moisture diffusion takes place when water molecules move from a high water vapor pressure to a low water vapor pressure.

**Desiccation-based dehumidification** is based on a desiccant dehumidification wheel, which is often coated with silica-gel (see Fig. A1.2). The air to be dried flows through the dehumidification wheel and moisture is removed. Subsequently, the dried air is delivered to the room. In order to prevent saturation of the desiccant, a heated air stream (reactivation air) is pulled through a protected (sealed) sector of the wheel in opposite direction. Reactivation air is heated by 15°C (59°F) to 20°C (68°F) and therefore has a low relative humidity. The water vapor can be directly exhausted to the outside or collected as a condensate in a suitable reservoir. Desiccant dehumidifiers are rarely used as mobile units; they are mostly used in air handling units.

**Dew point** is the temperature below which the water vapor in air condenses into liquid water.

**Displacement ventilation** (also called thermal displacement ventilation) is based on the fundamental principle that hot air rises. It is achieved by introducing relatively cold air – whose temperature is lower than the desired indoor temperature – at relatively low speed in the room/space. This air is then heated by heat sources placed at ground level, which causes it to rise. The formed convective air currents, transport the air upwards. The rising air is then removed from the zone at ceiling level.

**Electrostatic filtering** takes place by positively charging all particles present in the air in a so-called charging section of an HVAC system. The positively charged particulate contaminants are then removed by electrostatic attraction as the air passes through a series of negatively charged collecting plates.

**Ensemble** is an assembly of immovable and movable items of historic, artistic, scientific, or technical importance. Ensembles not only include buildings and their fittings, but also an assembly of objects and building, room, or place. An ensemble constitutes the material source of its own history in particular, and of the historic identity of society in general.

**Equilibrium moisture content** is the amount of moisture in a (hygroscopic) material, expressed as mass percent or volume percent when it is in equilibrium with the relative humidity of the surrounding air at a given temperature.

**Fatigue** is a phenomenon in which a material undergoes structural damage when subjected to cyclic loading (e.g. many relative humidity fluctuations). It can cause fracture even if the stress that develops within the material remains (far) below its yield or breaking point.

**Gesamtkunstwerk** is a creation (ensemble) of an architect/artist in which the building, furniture, silverware, wallpaper, and sometimes even the residents' clothing are designed as one.

**Gesso** is a mixture of water, animal glue, and gypsum (calcium sulphate). Gesso is the Italian word for 'chalk'. It is used as a ground (primer) to equalize a medium.

**Glass transition temperature** is the temperature at which a material undergoes a reversible transition from a rubbery state into brittle state, and *vice versa.*

**Gouache** is a painting made of pigments suspended in water. In contrast to watercolours the ground layer is not visible. The opacity of gouache is obtained by a higher ratio of pigment to water, and by mixing the water-based paint with an opaque white colour. It was earlier made of chalk mixed with gum Arabic, and since the mid-nineteenth century, zinc white was used.

**Gradient** is the spatial difference of the relative humidity and/or temperature across a given space. For instance, if the relative humidity in the centre of a room is 50%, and at a cold wall 65% the relative humidity gradient across the room is 15%.

**G-value (solar transmittance value)** is the same as Solar Heat Gain Coefficient (SHGC) used in the USA. It is the ratio of the total solar energy entering through the glass into a space and the incident solar energy. The G-value is a number between 0 and 1. A low G-value represents less heat gain.

**Half-life** is the time (green line in Fig. A1.3) needed for an object to undergo half of the complete (volume) change (red line in Fig. A1.3) when exposed to e.g. a changing relative humidity.

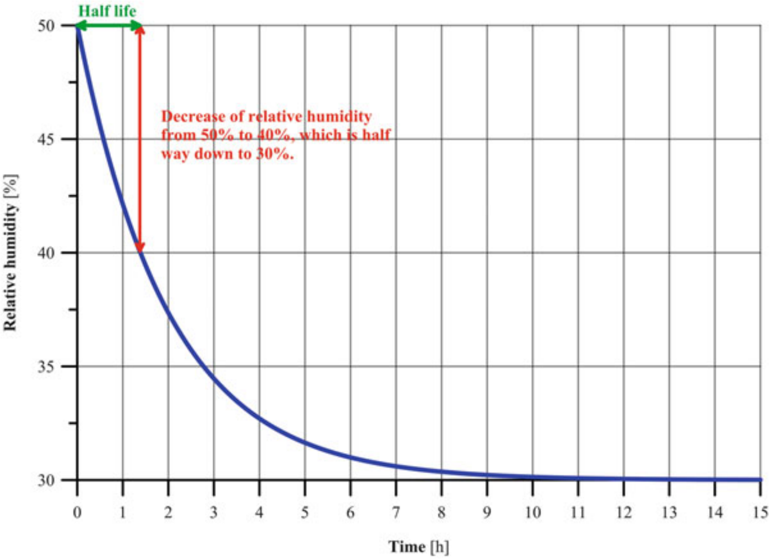


**Fig. A1.3** Schematic representation of the concept of half-life

**Hygroscopic materials** are materials that can absorb from or desorb/release moisture to the surrounding air. This process is often accompanied by mass and volume changes.

**Hygrostatic heating (*conservation heating*)** means that the relative humidity is regulated to the desired levels by adjusting the temperature. This means that the temperature is maintained at low levels to maintain a high relative humidity and the temperature is increased to reduce the relative humidity. This is in contrast with thermostatic heating, where the temperature is the main parameter to be controlled with changes in relative humidity as a result.

**Hysteresis** is the phenomenon whereby the relationship between input (stimulus) and effect depends not only on the magnitude of the input, but also on the direction in which it occurs. The difference between the equilibrium moisture content of wood measured during drying and during moisture uptake is an example of such phenomenon.

**Infiltration rate** is the uncontrolled outdoor air flow that penetrates through cracks, crevices, per unit time, divided by the net internal volume of the space.

**Interstitial condensation** occurs when warm, moist air (generally, from inside a building) diffuses into a wall, roof or floor and reaches dew point. This results in liquid water formed within the structure.

**Isothermal steam humidifier** works by heating a water reservoir using a heating element. The water vapor generated by heating at a constant temperature is then introduced into the air. The steam humidifier is commonly used in air handling units. It is hardly commercialized as a mobile unit. The water supply is often provided by a fixed service pipe.

**Isopleths** are lines of equal spore germination times or equal growth. The lowest isopleth for mould is abbreviated LIM.

**Mean radiant temperature** expresses the influence of the temperature of all surfaces surrounding on the thermal comfort of a person, depending on several factors such as angle of radiation and distance between the person and the surfaces.

**Moving average** of e.g. the relative humidity is obtained at a given point in time by taking the average value of previous relative humidity readings up to that point over the duration of the response time. The relative humidity response can also be approximated using a first order approach (see Eq. A5.3).

**Median** (or the 50th percentile) is the numeric value in the middle of a data set ordered from low to high.

**Microclimate** is a closed volume isolated from the environment in the zone (e.g. box, bag, showcase, corner, space behind a painting or cupboard). In this separated environment a climate can be created that is different from the climate in the zone due to humidity buffers or small humidification and/or dehumidification systems.

**Night ventilation** can be used to ventilate a building at night with relatively cold air, to cool the indoor air. It works only if the building can release enough heat during the night, which was accumulated during the day. This means that the

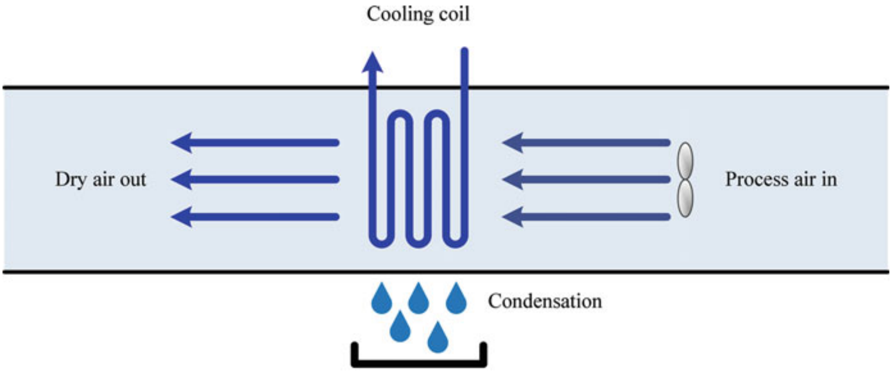


**Fig. A1.4** Schematic representation of refrigerant dehumidification

building must have enough thermal mass. In order to be efficient the ventilation should be high enough; four to six air exchanges per hour.

**Predicted Mean Vote index** predicts the average thermal sensation of a large group of people according to the ASHRAE scale from −3 being too cold, to +3 being too hot.

**Predicted Percentage Dissatisfied index** is an measure to predict the mean response of a larger group of people according to the ASHRAE thermal sensation scale, in which +3 indicates people being too hot, +2 indicates people being too warm, +1 indicates people being slightly too warm, 0 indicates people being neutral, −1 indicates people being slightly too cool, −2 indicates people being too cool, −3 indicates people being too cold.

**Proofed relative humidity fluctuations** are the relative humidity fluctuations that the object or collection has been exposed to in the past that were harmless. They provide an indication of the magnitude of future risks of mechanical damage. According to this concept, the risk of fracture or delamination due to relative humidity fluctuations is not significant *unless* future relative humidity fluctuations are larger than those already experienced in the past.

**Radiation** is the amount of energy emitted as particles or waves by a surface.

**Recirculation rate** is the volume of air taken from the climatised zone that is transported back to the climate system and re-entered into the zone, divided by the net internal volume of the zone.

**Refrigerant air drying** takes place by cooling the air below the dew point temperature. Due to condensation, moisture is extracted from the air (see Fig. A1.4). The dehumidified air is then heated up to room temperature and delivered to the desired areas. The condensed water is collected in a suitable tray or drained with a hose.

**Relative humidity** is the percentage of water vapor with respect to the maximum possible amount of water vapor in the air at a given temperature and air pressure.

**Relative usability** is a term used to indicate the time during which a material (object) can be used, consulted, and/or displayed in a museum context. The term 'lifetime' is often used in other publications to express the same concept.

**Response time** is the amount of time an object requires to equilibrate for 95% (Martens, 2012) with new environmental conditions.

**Risk** is the likelihood of losing an amount of (cultural) value.

**Set point** is the value to which the climate control system is set; generally the annual average. Temperature and relative humidity will fluctuate around this central value.

**Significance** is the sum of all values: historic, aesthetic, scientific, and social, that an object has for past, current, and future generations. It also refers to the sum of elements that contribute to the meaning of the object, i.e. its context, history, condition, provenance, uniqueness and use.

**Specific hygroscopic moisture capacity** is the amount of moisture that can be absorbed by a material at a given relative humidity.

**Stress relaxation** (or **relaxation**) is the decrease of stress within materials under constant strain with time.

**Sun path diagrams** show the annual changes in the path of the sun for a specific geographical location through the sky in a two dimensional diagram.

**Tensile strength** is the resistance of a material to a force, measured as the maximum strain the material can withstand without breaking.

**Thermal bridge** (cold bridge) is a local high energy transfer (see figure below on the right, large arrows) due to a penetration of the insulation layer by a highly conductive or non-insulating material (figure on the left). This will result in high surface temperatures (red) on the outside of the thermal bridge and low surface temperature (purple) on the inside of the thermal bridge (figure in the middle).

**Thermal expansion coefficient** describes the volume change of an object (material) due to a change in temperature.

**Time weighted preservation index** is a measure by which the relative rate of chemical decay of materials/collections under different temperatures and relative humidities can be expressed.

**Ventilation rate** is the desired or controlled outdoor air flow that enters by opening doors, windows, air handling units and other ventilation options per unit time, divided by the net internal volume of the space.

**Volumetric flow rate** is the volume of air per unit time that is introduced into a given space.

**Water activity** is related to the amount of free moisture in a material. For practical reasons the surface relative humidity is often used as a measure for the water activity.

**Yield point** in a stress-strain curve is the moment at which the elastic limit of the material is exceeded. Within the elastic deformation range, the material can return to its original shape upon removal of stress. When strained beyond its elastic limit, i.e. the yield point, the material becomes irreversibly deformed.

## Appendix 2: Managing Risks to Collections

Before proceeding with the choice of a specific climate control system it is essential to consider the specific risks that will be eliminated or reduced by controlling the indoor climate and weigh these against all (possible) risks to the collection. A structured way to do this is by collection risk management.[1] Using the risk management method, risks are first identified, then analysed (quantified) and evaluated (weighed against each other). Going through these steps, which allow prioritization, e.g. based on the magnitude of risks, development and selection of alternatives to reduce (the highest or several small) risks. An incorrect (museum) indoor climate should therefore be considered within the larger framework of all agents of deterioration to the collection (see also Fig. A2.1), which include:

### *Physical Forces*

Physical forces encompass all types of damage caused by vibration, abrasion, shock, and gravity. For instance, poor support of objects or incorrect packing during transportation can lead to breakage. Much of the mechanical damage to objects can be traced to improper handling and use, but there are other causes such as touching by visitors, use of abrasive polishers, explosions, collapsing buildings, and natural disasters, such as earthquakes.

### *Fire*

This includes the occurrence, spreading, and intensification of a fire. It can be a blast, total fire, a fire confined to a compartment, or a small localized fire, e.g. in a trash bin or due to a toppling candle. The most common causes of fire are short circuit in the electrical system, arson, and open flames. Possible types of damage include scorching, charring, melting, or total loss of objects. There is also sooting and collateral damage caused by fire extinguishing procedures and agents. The impact depends strongly on the fire response time, i.e., on the effectiveness of fire detection, notification, response, and control, as well as on the extinguishing agents used.

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[1] (a) Waller R (2002) A risk model for collection preservation. In Vontobel R (Ed) *ICOM committee for conservation 13th triennial meeting Rio De Janeiro, 22–27 September 2002*: 102–107 (b) Waller R (2003) Cultural property risk analysis model: development and application to preventive conservation at the Canadian Museum of Nature.Dissertation *Göteborg University.*

## *Criminals and Vandals*

This covers deliberately caused damage to or loss of objects, including losses that could be prevented by proper security. The most common are burglary, theft during opening hours, internal theft (by staff), vandalism, and graffiti. Especially valuable objects have a relatively high chance of being stolen. But (small) objects that are within reach certainly cannot be considered safe because of 'souvenir hunters'.

## *Water*

The term refers to liquid water. Water incidents in a museum can occur in different ways, e.g. inundations resulting from natural disasters, breakage of water pipes or drains, or roof leakage. In addition to the damage caused by the wetting of materials, extensive damage can sometimes occur when wet collections are dried.

## *Pests*

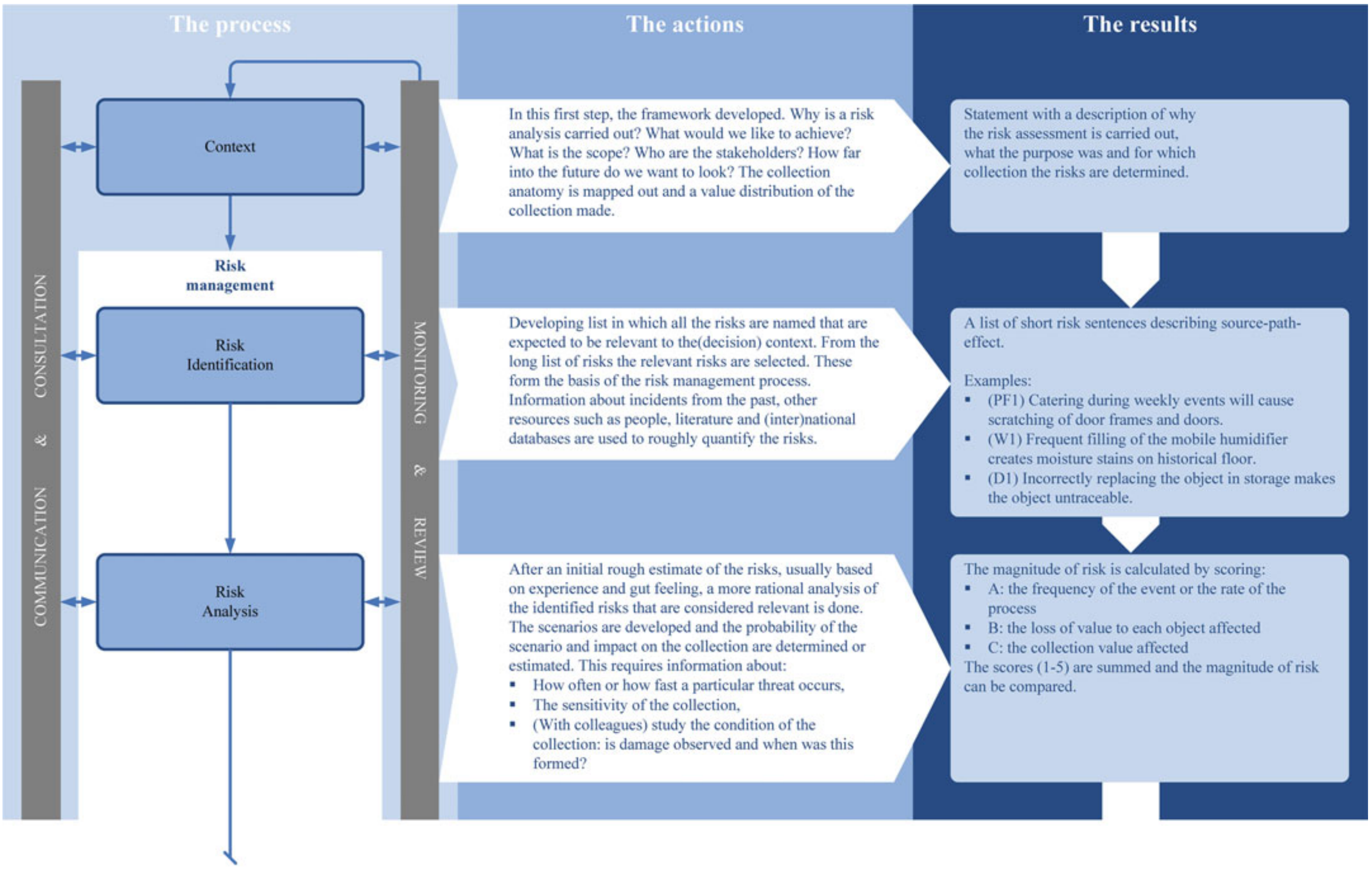
There are several distinct types of pests, ranging from rodents to birds, bats, and insects. Pests can reach the collection through open windows and doors, or other openings in the building. They are often brought inside the museum together with newly acquired or loaned objects.

## *Pollutants*

It is possible to make a distinction between pollutants that are airborne, spilt/leaked liquids, solid fat and dirt such as typically found in fingerprints, and inappropriate materials used for maintenance and conservation-restoration. Air pollution can be divided into harmful gasses and dust, which can be generated both outside and inside the museum, e.g. by construction materials or by objects themselves.

## *Radiation*

Light can cause damage to objects. Daylight and light generated by electrical sources (lamps) in the museum are composed of visible light, ultraviolet and infrared radiation. Dyes fade, paper, varnishes and lacquers yellow, wood can yellow or bleach, and some chemical processes are accelerated.



In this first step, the framework developed. Why is a risk analysis carried out? What would we like to achieve? What is the scope? Who are the stakeholders? How far into the future do we want to look? The collection anatomy is mapped out and a value distribution of the collection made.

Statement with a description of why the risk assessment is carried out, what the purpose was and for which collection the risks are determined.

Developing list in which all the risks are named that are expected to be relevant to the(decision) context. From the long list of risks the relevant risks are selected. These form the basis of the risk management process. Information about incidents from the past, other resources such as people, literature and (inter)national databases are used to roughly quantify the risks.

A list of short risk sentences describing source-path-effect.

Examples:

- (PF1) Catering during weekly events will cause scratching of door frames and doors.
- (W1) Frequent filling of the mobile humidifier creates moisture stains on historical floor.
- (D1) Incorrectly replacing the object in storage makes the object untraceable.

After an initial rough estimate of the risks, usually based on experience and gut feeling, a more rational analysis of the identified risks that are considered relevant is done. The scenarios are developed and the probability of the scenario and impact on the collection are determined or estimated. This requires information about:

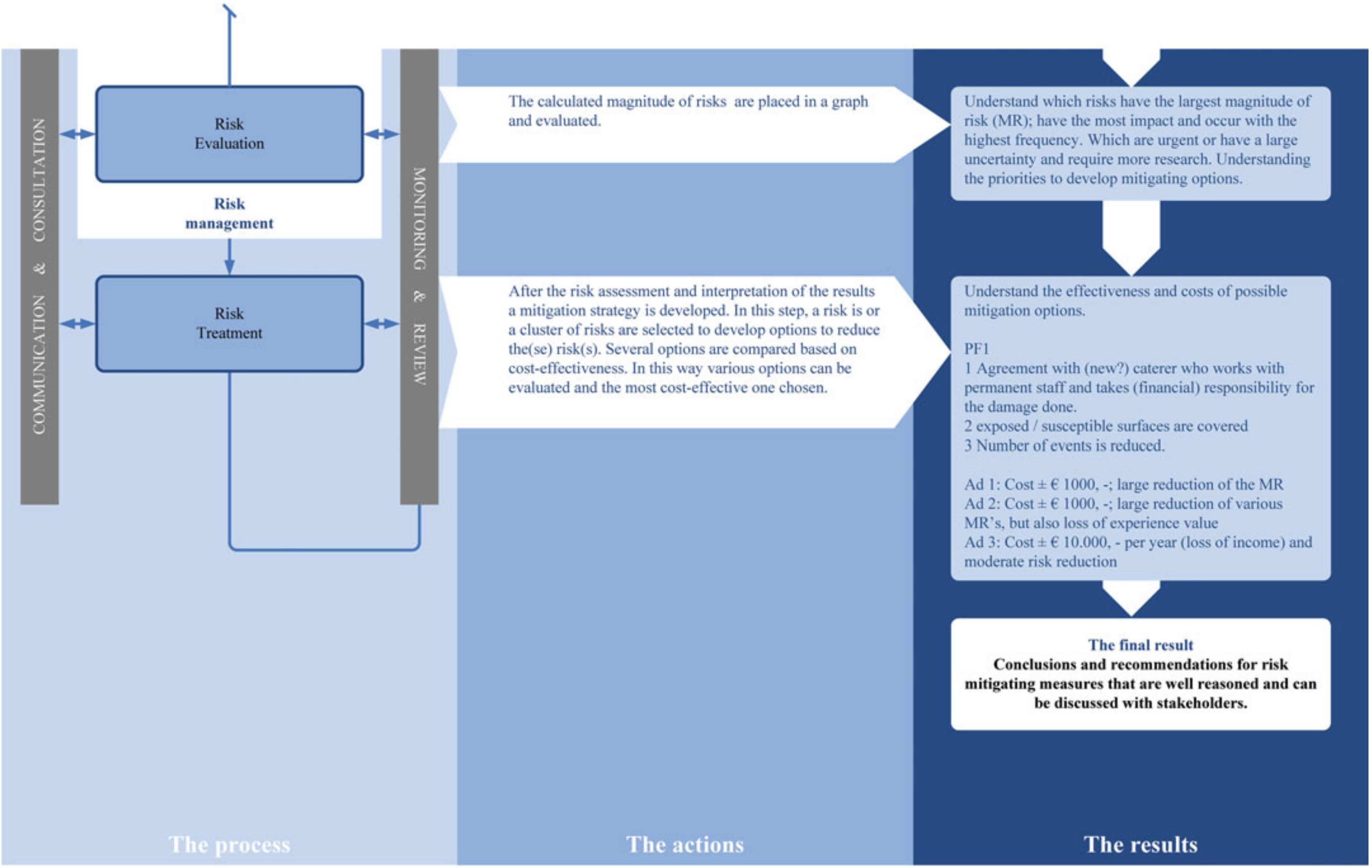
- How often or how fast a particular threat occurs,
- The sensitivity of the collection,
- (With colleagues) study the condition of the collection: is damage observed and when was this formed?

The magnitude of risk is calculated by scoring:

- A: the frequency of the event or the rate of the process
- B: the loss of value to each object affected
- C: the collection value affected

The scores (1-5) are summed and the magnitude of risk can be compared.

**Fig. A2.1** The risk management process



The calculated magnitude of risks are placed in a graph and evaluated.

After the risk assessment and interpretation of the results a mitigation strategy is developed. In this step, a risk is or a cluster of risks are selected to develop options to reduce the(se) risk(s). Several options are compared based on cost-effectiveness. In this way various options can be evaluated and the most cost-effective one chosen.

Understand which risks have the largest magnitude of risk (MR); have the most impact and occur with the highest frequency. Which are urgent or have a large uncertainty and require more research. Understanding the priorities to develop mitigating options.

Understand the effectiveness and costs of possible mitigation options.

PF1
1 Agreement with (new?) caterer who works with permanent staff and takes (financial) responsibility for the damage done.
2 exposed / susceptible surfaces are covered
3 Number of events is reduced.

Ad 1: Cost ± € 1000, -; large reduction of the MR
Ad 2: Cost ± € 1000, -; large reduction of various MR's, but also loss of experience value
Ad 3: Cost ± € 10.000, - per year (loss of income) and moderate risk reduction

**The final result**
**Conclusions and recommendations for risk mitigating measures that are well reasoned and can be discussed with stakeholders.**

**Fig. A2.1** (continued)

## *Incorrect Temperature*

Is the subject of this publication.

## *Incorrect Relative Humidity*

Is the subject of this publication.

## *Dissociation*

Part of the value of many objects derives from the information available about them. If this information is lost (e.g. by the loss of documentation, computer data, or unwritten knowledge), the object loses value. Objects can also go out of sight and out of mind because of neglect or negligence. It also happens that objects 'disappear' as a result of their misplacement in storage, etc.

### Roadmap to Risk Assessment

**Identification** In a brainstorm session risks are developed; for each agent of deterioration several risk sentences are developed that describe the source of the agent, the path it follows to the collection and the effect on the material(s). from the long list, a short list with relevant risks can be extracted that can subsequently be analysed.

**Analysis** A number of (worst case) scenarios can be developed for each of the 10 aforementioned agents of deterioration, plausibly describing how damage can occur in a given museum context. The following questions are then answered for each scenario:
A-score: What is the probability for that scenario to occur?

- For events: How often does the event occur, or what is the frequency of the events, or what is the time interval between events?
- For processes: How long does it take before damage becomes visible?

B-score: How much value is lost for each affected object?
C-score: How much collection value is affected?

**Evaluation** By numerically scoring A, B and C on a scale from 1 to 5 it is possible to obtain a (semi) quantitative overview of the relative importance among all analysed risks. Needs and priorities for mitigating a specific risk or cluster of risks can be established by evaluating the magnitude of the risks.

**Mitigation** Options to reduce the risks are developed and their cost-effectiveness calculated.

# Appendix 3: The Psychrometric Chart

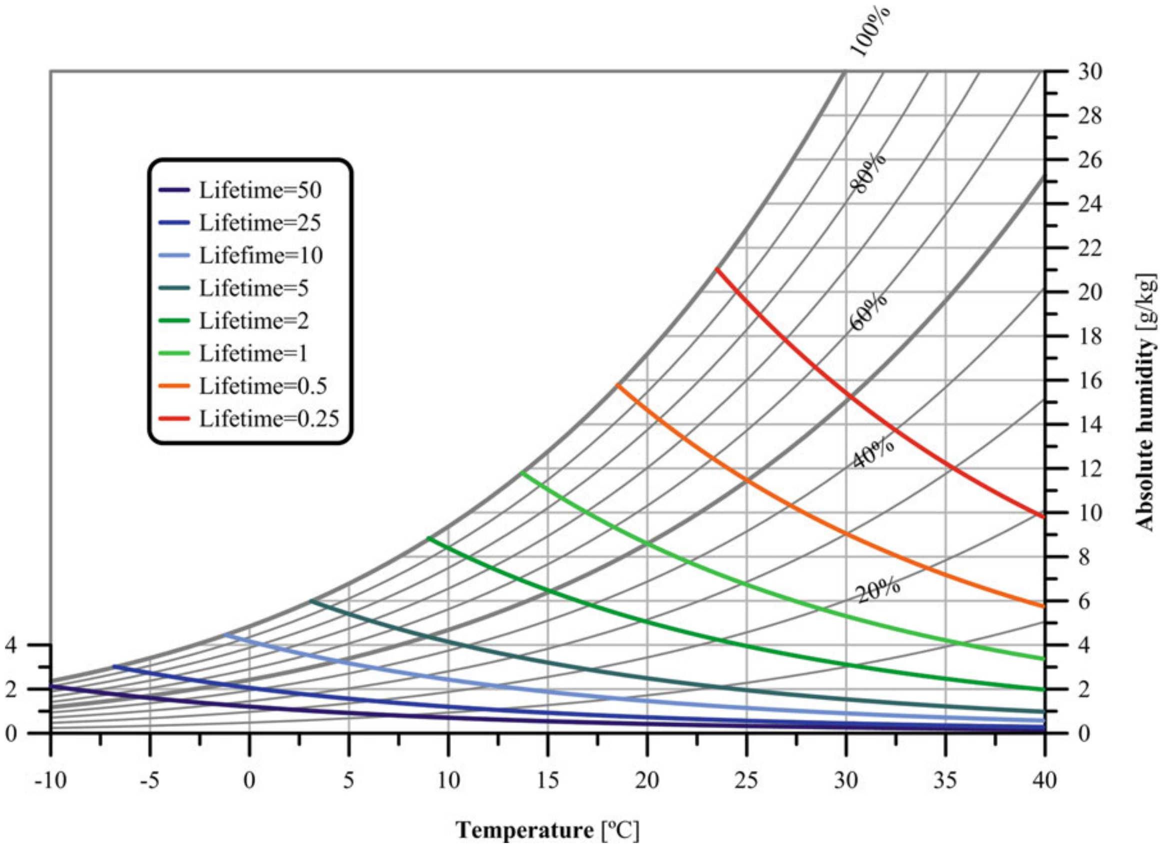
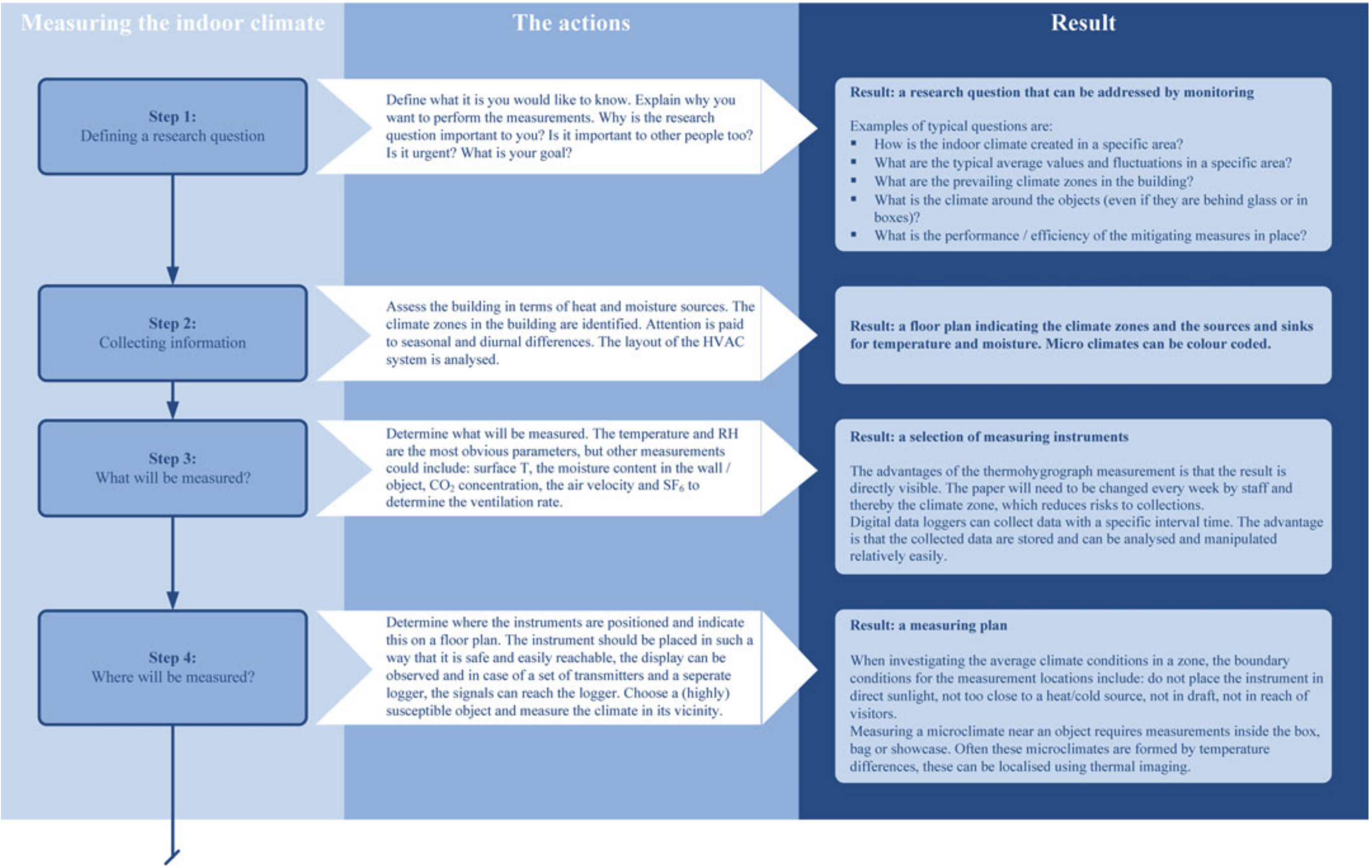


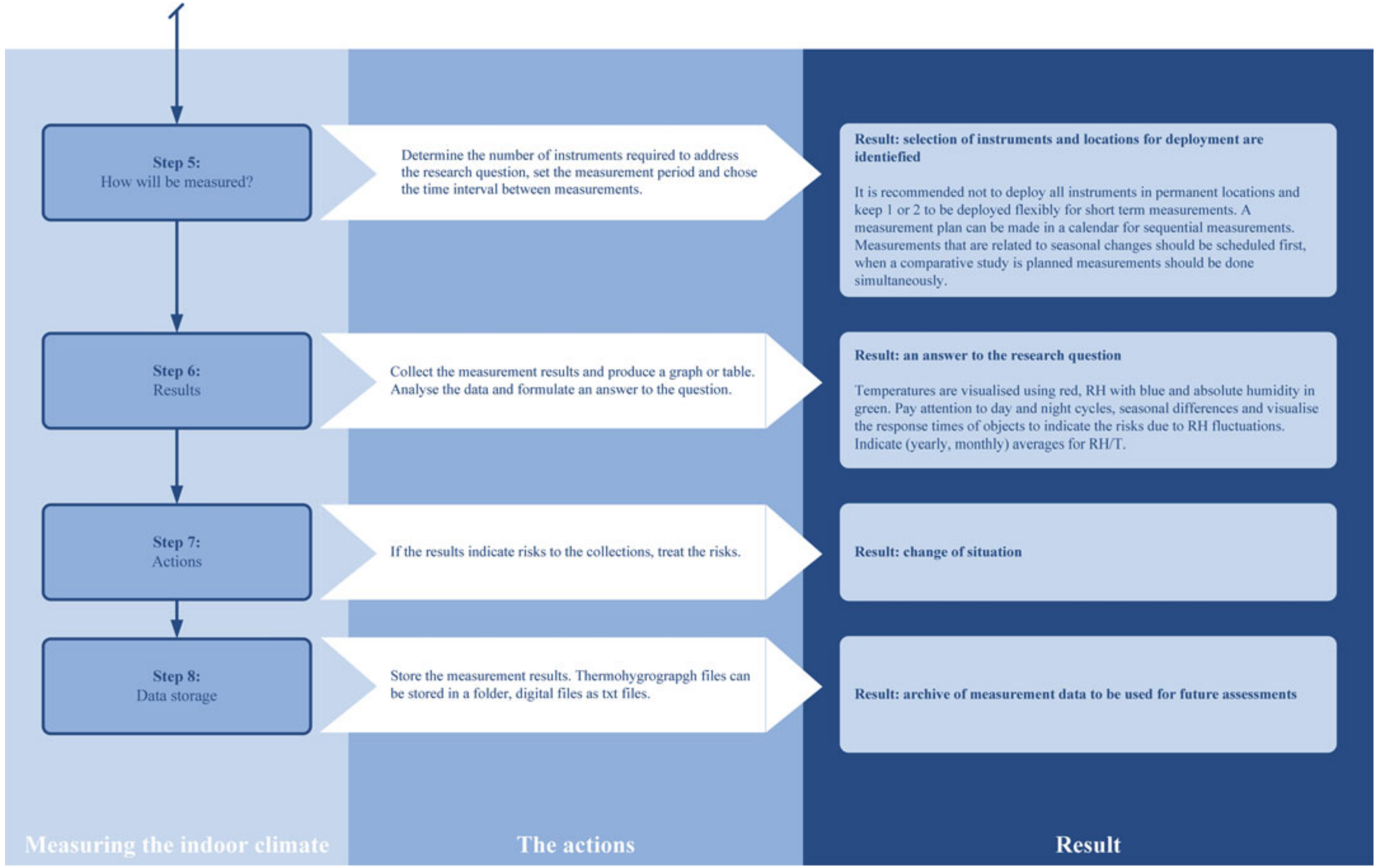
**Fig. A3.1** The psychrometric chart with Lines of equal Relative Usable Lifetimes with respect to reference conditions of a relative humidity of 50 % and a temperature of 20 °C

# Appendix 4: Measuring the Indoor Climate



| Measuring the indoor climate | The actions | Result |
|---|---|---|
| **Step 1:**<br>Defining a research question | Define what it is you would like to know. Explain why you want to perform the measurements. Why is the research question important to you? Is it important to other people too? Is it urgent? What is your goal? | **Result: a research question that can be addressed by monitoring**<br>Examples of typical questions are:<br>▪ How is the indoor climate created in a specific area?<br>▪ What are the typical average values and fluctuations in a specific area?<br>▪ What are the prevailing climate zones in the building?<br>▪ What is the climate around the objects (even if they are behind glass or in boxes)?<br>▪ What is the performance / efficiency of the mitigating measures in place? |
| **Step 2:**<br>Collecting information | Assess the building in terms of heat and moisture sources. The climate zones in the building are identified. Attention is paid to seasonal and diurnal differences. The layout of the HVAC system is analysed. | **Result: a floor plan indicating the climate zones and the sources and sinks for temperature and moisture. Micro climates can be colour coded.** |
| **Step 3:**<br>What will be measured? | Determine what will be measured. The temperature and RH are the most obvious parameters, but other measurements could include: surface T, the moisture content in the wall / object, $CO_2$ concentration, the air velocity and $SF_6$ to determine the ventilation rate. | **Result: a selection of measuring instruments**<br>The advantages of the thermohygrograph measurement is that the result is directly visible. The paper will need to be changed every week by staff and thereby the climate zone, which reduces risks to collections.<br>Digital data loggers can collect data with a specific interval time. The advantage is that the collected data are stored and can be analysed and manipulated relatively easily. |
| **Step 4:**<br>Where will be measured? | Determine where the instruments are positioned and indicate this on a floor plan. The instrument should be placed in such a way that it is safe and easily reachable, the display can be observed and in case of a set of transmitters and a seperate logger, the signals can reach the logger. Choose a (highly) susceptible object and measure the climate in its vicinity. | **Result: a measuring plan**<br>When investigating the average climate conditions in a zone, the boundary conditions for the measurement locations include: do not place the instrument in direct sunlight, not too close to a heat/cold source, not in draft, not in reach of visitors.<br>Measuring a microclimate near an object requires measurements inside the box, bag or showcase. Often these microclimates are formed by temperature differences, these can be localised using thermal imaging. |

**Fig. A4.1** A step by step action plan for measuring the indoor climate



Determine the number of instruments required to address the research question, set the measurement period and chose the time interval between measurements.

**Result: selection of instruments and locations for deployment are identiefied**

It is recommended not to deploy all instruments in permanent locations and keep 1 or 2 to be deployed flexibly for short term measurements. A measurement plan can be made in a calendar for sequential measurements. Measurements that are related to seasonal changes should be scheduled first, when a comparative study is planned measurements should be done simultaneously.

Collect the measurement results and produce a graph or table. Analyse the data and formulate an answer to the question.

**Result: an answer to the research question**

Temperatures are visualised using red, RH with blue and absolute humidity in green. Pay attention to day and night cycles, seasonal differences and visualise the response times of objects to indicate the risks due to RH fluctuations. Indicate (yearly, monthly) averages for RH/T.

If the results indicate risks to the collections, treat the risks.

**Result: change of situation**

Store the measurement results. Thermohygrograpgh files can be stored in a folder, digital files as txt files.

**Result: archive of measurement data to be used for future assessments**

**Fig. A4.1** (continued)

## Appendix 5: Calculation of Expected Lifetime of Objects

The equations used to describe the relationship between the rate of chemical degradation due to hydrolysis and, respectively, the relative humidity and the temperature can be combined as follows:

$$k_{RH} = RH^{1.3} \; and \;\; k_T = A \cdot e^{\frac{-E_A}{RT}} \; into \;\; k_{total} = k_T \times k_{RH} = RH^{1.3} \times A \cdot e^{\frac{-E_A}{RT}} \quad \text{(A5.1)}$$

Since the expected usability (U) is inversely proportional to the reaction rate (k), it can be expressed as a function of relative humidity and temperature:

$$U = \frac{1}{k_{total}} = \frac{1}{RH^{1.3} \times A \cdot e^{\frac{-E_A}{RT}}} = RH^{-1.3} \times A \cdot e^{\frac{E_A}{RT}} \quad \text{(A5.2)}$$

By selecting a reference relative humidity and temperature, the relative usability ($RU_x$) can be assessed. It is practical to choose a relative humidity of 50% and a temperature of 20°C as a (museum) reference climate, and to calculate how different relative humidities and temperatures affect the expected usability of objects.

$$\frac{RU_x}{U_{ref}} = \frac{RH_x^{-1.3} \times A \cdot e^{\frac{E_A}{RT_x}}}{RH_{ref}^{-1.3} \times A \cdot e^{\frac{E_A}{RT_{ref}}}} = \left(\frac{RH_x}{RH_{ref}}\right)^{-1.3} \times \frac{A \cdot e^{\frac{E_A}{RT_x}}}{A \cdot e^{\frac{E_A}{RT_{ref}}}}$$

$$= \left(\frac{RH_{ref}}{RH_x}\right)^{1.3} \times e^{\frac{E_A}{R}\left(\frac{1}{T_x} - \frac{1}{T_{ref}}\right)} \quad \text{(A5.3)}$$

Introducing a reference relative humidity ($RH_{ref} = 50\%$) and a reference temperature ($T_{ref} = 20°C$ (293 K)) gives:

$$\frac{RU_x}{U_{50\%/293K}} = \left(\frac{50\%}{RH_x}\right)^{1.3} \times e^{\frac{E_A}{R}\left(\frac{1}{T_x} - \frac{1}{293}\right)} \quad \text{(A5.4)}$$

The relative usability can now be calculated for different climate conditions by introducing the corresponding temperature and relative humidity values. The lines for the different RU's shown in the psychrometric chart (Figs. 4.22 and A3.1) are obtained by fixing the relative usability value and then finding the pairs of relative humidity and T values that yield the same RU value:

$$RH_x = 50\% \times \sqrt[1.3]{\frac{RU}{e^{\frac{E_A}{R}\left(\frac{1}{T_x} - \frac{1}{293}\right)}}} \quad \text{(A5.5)}$$

where:

RU = the relative usability,
$E_A$ = activation energy (in J.mol$^{-1}$, but often presented in the literature in kJ.mol$^{-1}$),
R = gas constant (8.314 J.K$^{-1}$.mol$^{-1}$),
T = temperature (K).

In order to use temperature values in °C instead of Kelvin, the equation can be rewritten as:

$$RH_x = 50\% \times \sqrt[1.3]{\frac{RU}{e^{\frac{E_A}{R}\left(\frac{1}{T_x+273}-\frac{1}{293}\right)}}} \tag{A5.6}$$

## Appendix 6: Conversion of Relative Humidity into Absolute Humidity

In order to make a psychrometric chart it is necessary to calculate the absolute humidity from relative humidity and temperature values, which is not straightforward. Different equations must be combined to arrive at a direct relationship between the three variables. When searching for moisture sources or sinks it is possible to use these equations to independently calculate the absolute humidity from relative humidity and temperature readings.

For T > 0°C, the following equations apply[2]:

$$p_{sat} = 611 \cdot e^{\left(\frac{17.08\theta}{234.18+\theta}\right)} \text{ and } p_v = p_{sat} \cdot \varphi \text{ and } x = \frac{611 \cdot p_v}{101300 - p_v} \tag{A6.1}$$

where:

$p_{sat}$ = saturation vapor pressure (Pa),
$\theta$ = temperature (°C),
$p_v$ = partial vapor pressure,
$\varphi$ = dimensionless relative humidity,
$x$ = absolute humidity (g water/kg air).

These three equations can be combined into:

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[2] Schellen HL (2002) Heating monumental churches, Indoor climate and preservation of cultural heritage. Dissertation, Technical Universtity Eindhoven. NB For temperatures of 0 °C and below a different relationship between the saturation vapor pressure and temperature applies.

$$\mathrm{x} = \frac{611 \cdot [0.01\,\mathrm{p_{sat}} \cdot]}{101300 - [0.01\,\mathrm{p_{sat}} \cdot]} \tag{A6.2}$$

and after introducing $p_{sat}$:

$$\mathrm{x} = \frac{611 \cdot \left[0.01 \cdot 611 \cdot \mathrm{e}^{\left(\frac{17.08\theta}{234.18+\theta}\right)}\right]}{101300 - \left[0.01 \cdot 611 \cdot \mathrm{e}^{\left(\frac{17.08\theta}{234.18+\theta}\right)}\right]} = \frac{3733.21 \cdot \mathrm{e}^{\left(\frac{17.08\theta}{234.18+\theta}\right)}}{101300 - \left[6.11 \cdot \mathrm{e}^{\left(\frac{17.08\theta}{234.18+\theta}\right)}\right]} \tag{A6.3}$$

The unit used to express *x* is ‘grams of water per kilogram of air’. In order to convert it into ‘grams of water per cubic meter of air’ (which is useful to have a sense of the amount of moisture in showcases), the result of the calculation should be multiplied by the density of air at room temperature: $\rho = 1.29\ \mathrm{kg/m^3}$, as can be seen in equation

$$\mathrm{x}\ \left[\frac{\mathrm{g}}{\mathrm{kg}}\right] \cdot \rho \left[\frac{\mathrm{kg}}{\mathrm{m^3}}\right] = \mathrm{x}\left[\frac{\mathrm{g}}{\mathrm{m^3}}\right] \tag{A6.4}$$

## Appendix 7: Schematic Representation of Relative Humidity Conditions in Climate Classes AA, A, and B

There is much confusion concerning the quantitative interpretation of the ASHRAE climate classes. Comparing measured climate data with the numerical ASHRAE classification as presented in Table 4.8 is quite difficult. Therefore a schematic representation of the expected behaviour of relative humidity and temperature in climate classes AA (see Fig. A7.1), A (see Figs. A7.2 and A7.3), and B (see Fig. A7.4) is provided below.

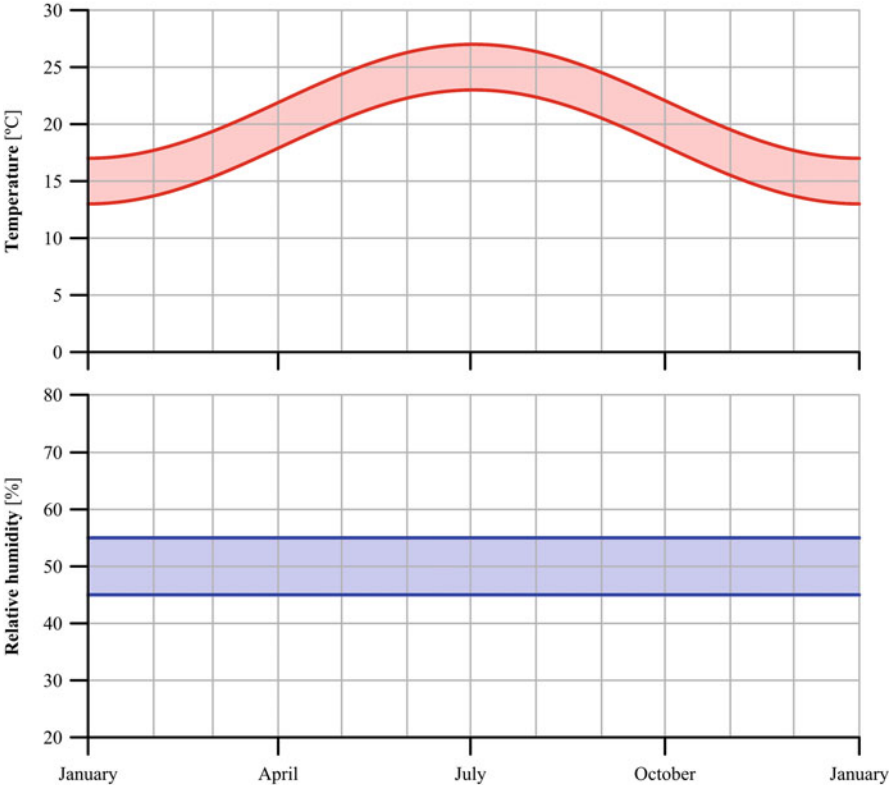

**Fig. A7.1** ASHRAE climate class AA

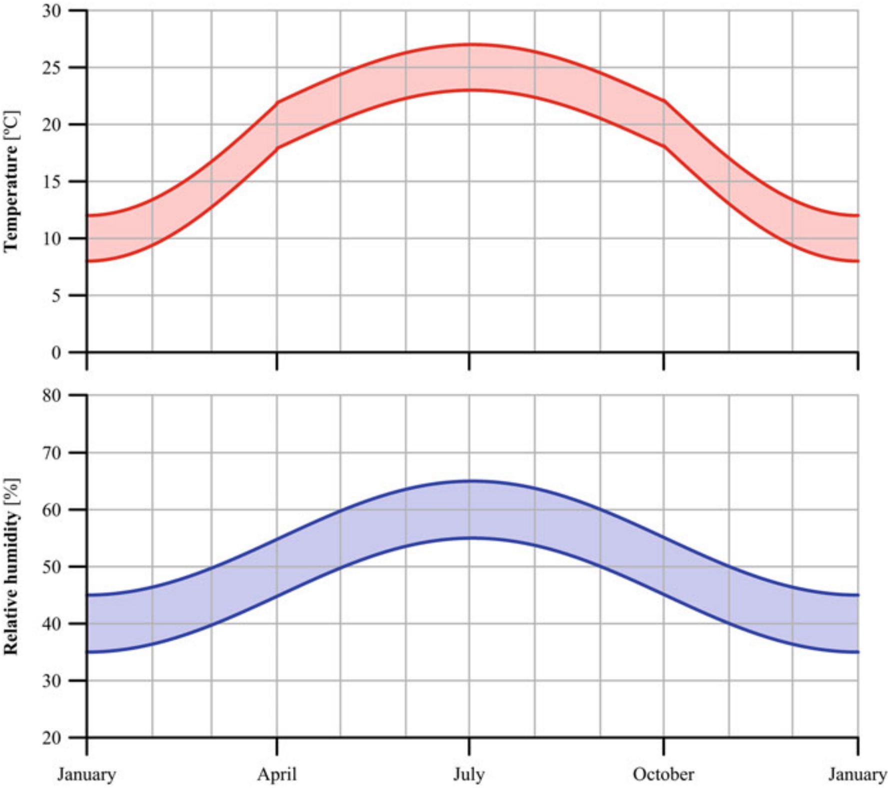

**Fig. A7.2** ASHRAE climate class As, accepting a seasonal relative humidity changes

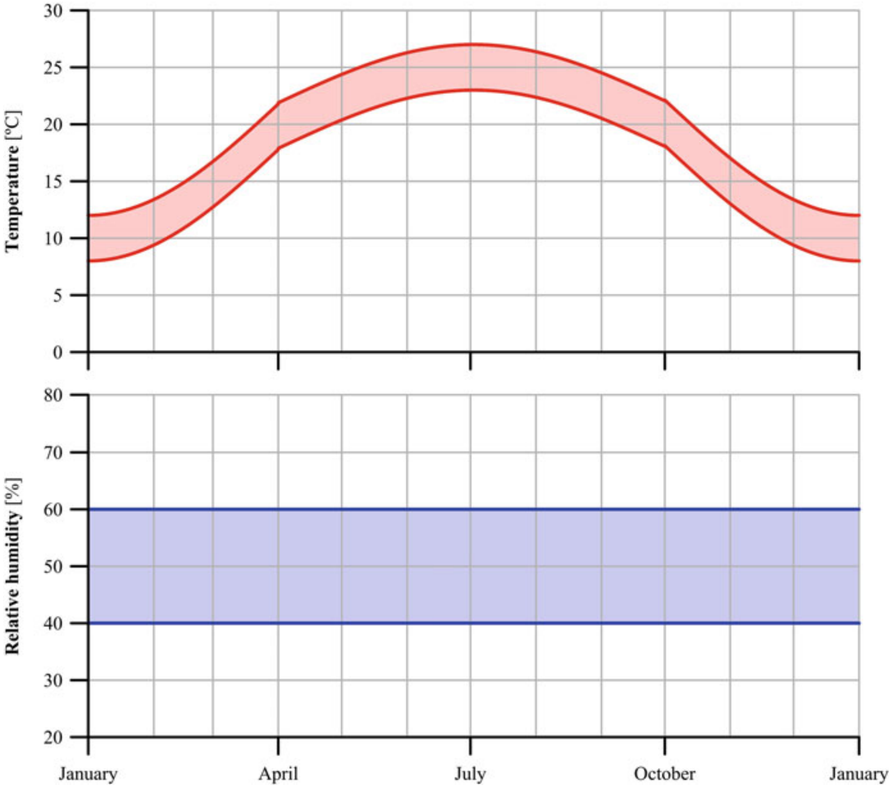

Fig. A7.3 ASHRAE climate class A, accepting only short relative humidity changes

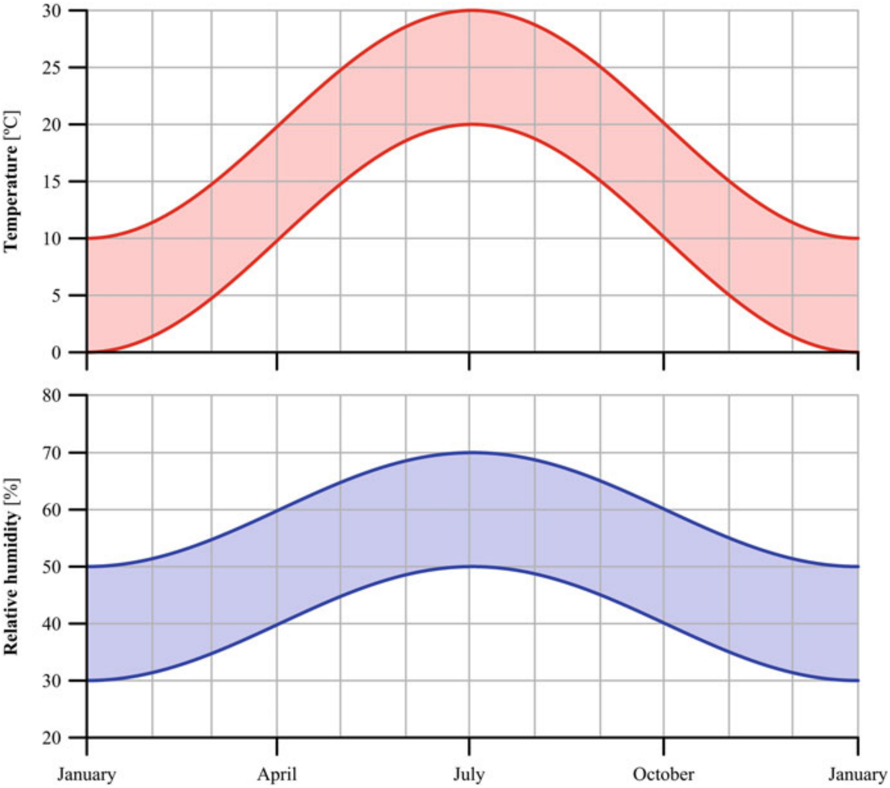

**Fig. A7.4** ASHRAE climate class B

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