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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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.

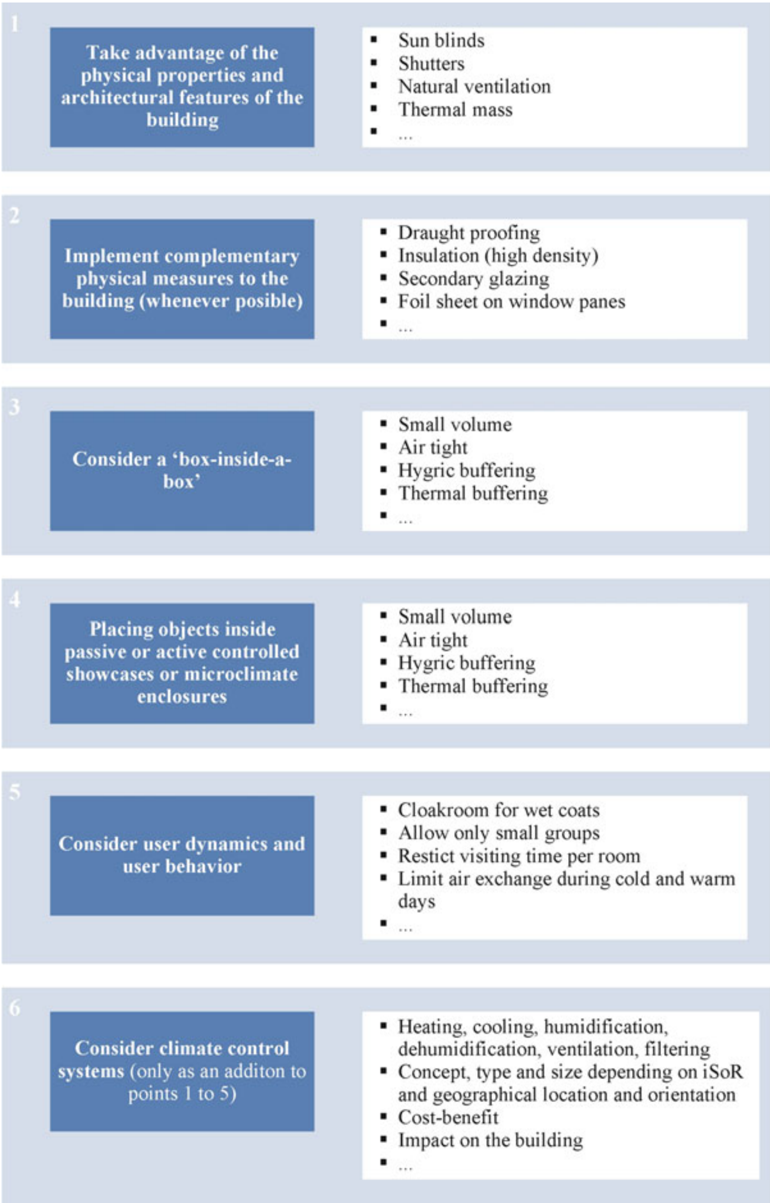

Fig. 9.1 Six steps to develop a climate control strategies

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

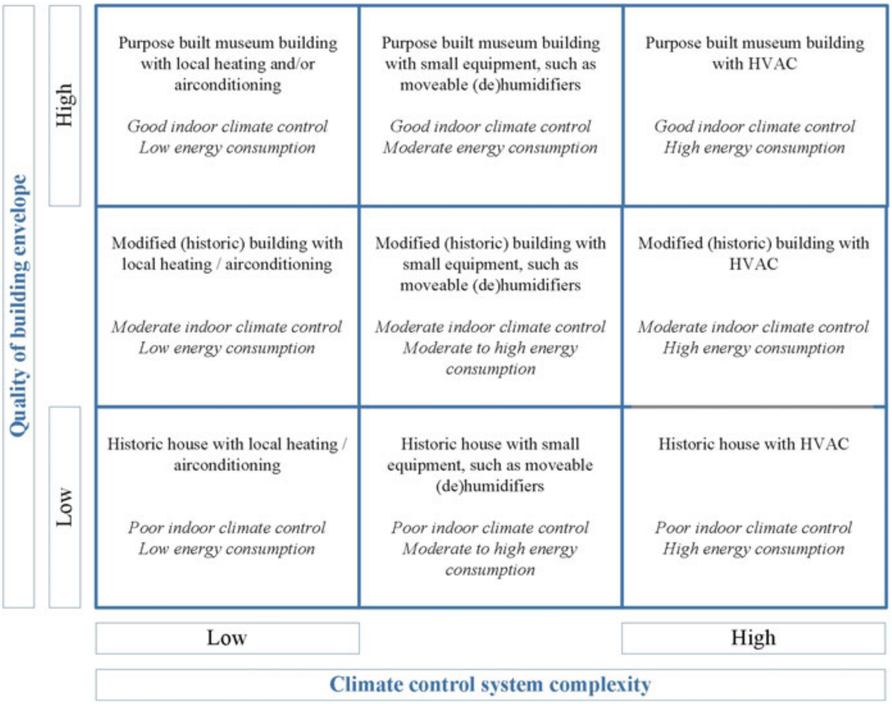

Fig. 9.2 The indoor climate as a function of building physics and complexity of the climate control system

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

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

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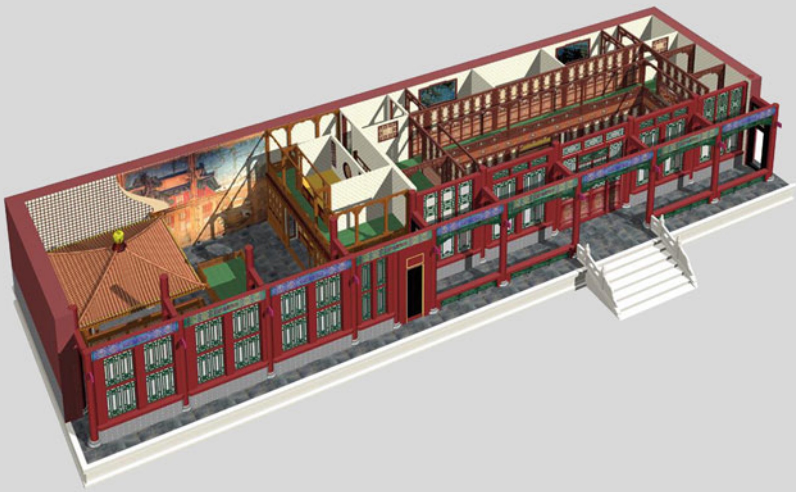

Fig. 9.7 The studio of exhaustion from diligent service. On the *left side* the theater with mural paintings on silk and the wood resembling bamboo. On the *right side* the entrance to the reception area containing the embroidered silk and the bamboo veneers (Drawing: Prof. Liu Chang of the Tsinghua 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

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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

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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

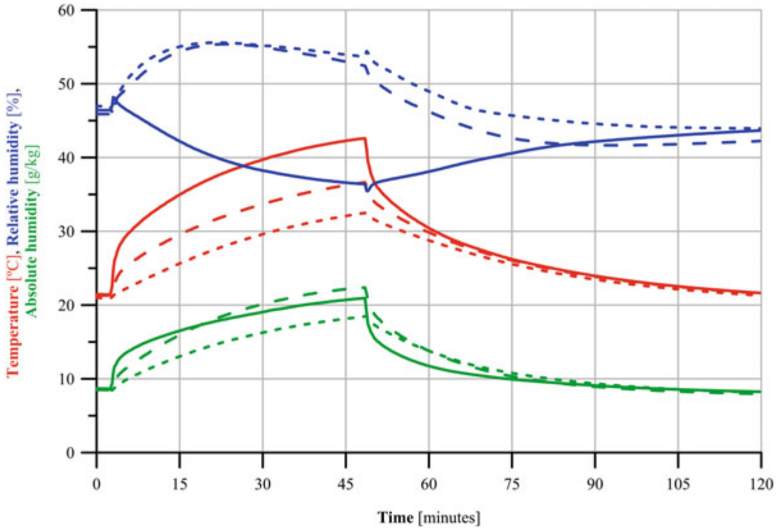

Fig. 9.9 The relative humidity, absolute humidity and temperature profiles inside a microclimate box and behind a pastel when exposed to infrared radiation. *Continuous line* shows the climate behind the black painted surface, the *dashed line* the climate behind the white painted surface and *dotted* 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

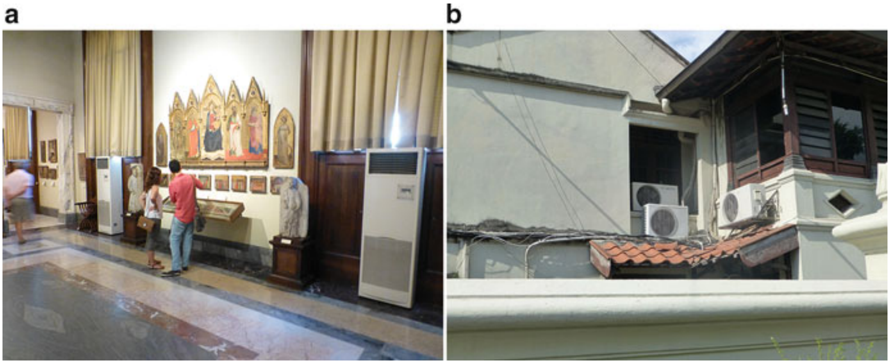

Fig. 9.13 A typical local cooling unit with the evaporator (evaporator coil, expansion devise, and blower) on the inside (**a**) (Roma, The Vatican Museums) and condensing unit (condensing coil, compressor and fan) on the outside (**b**) (Jogyakarta, Museum Sonobodoyo)

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.

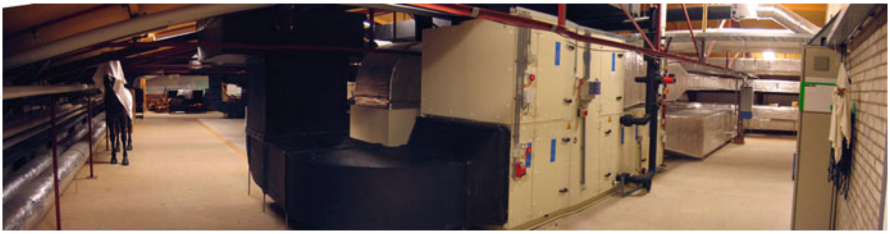

Fig. 9.14 Air handling unit in a mechanical room

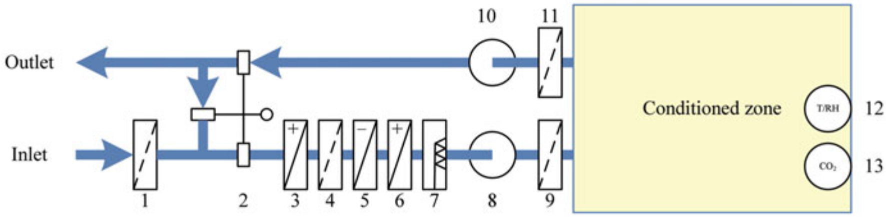

Fig. 9.15 Schematic representation of a climate control system, including: (*1*) Coarse-grade filter (F7); (*2*) Motorized mixing valve; (*3*) Pre heater; (*4*) Chemically active filter; (*5*) Cooler/dehumidifier; (*6*) Heater; (*7*) Humidifier; (*8*) Supply fan; (*9* and *11*) Fine-grade filter (F9); (*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

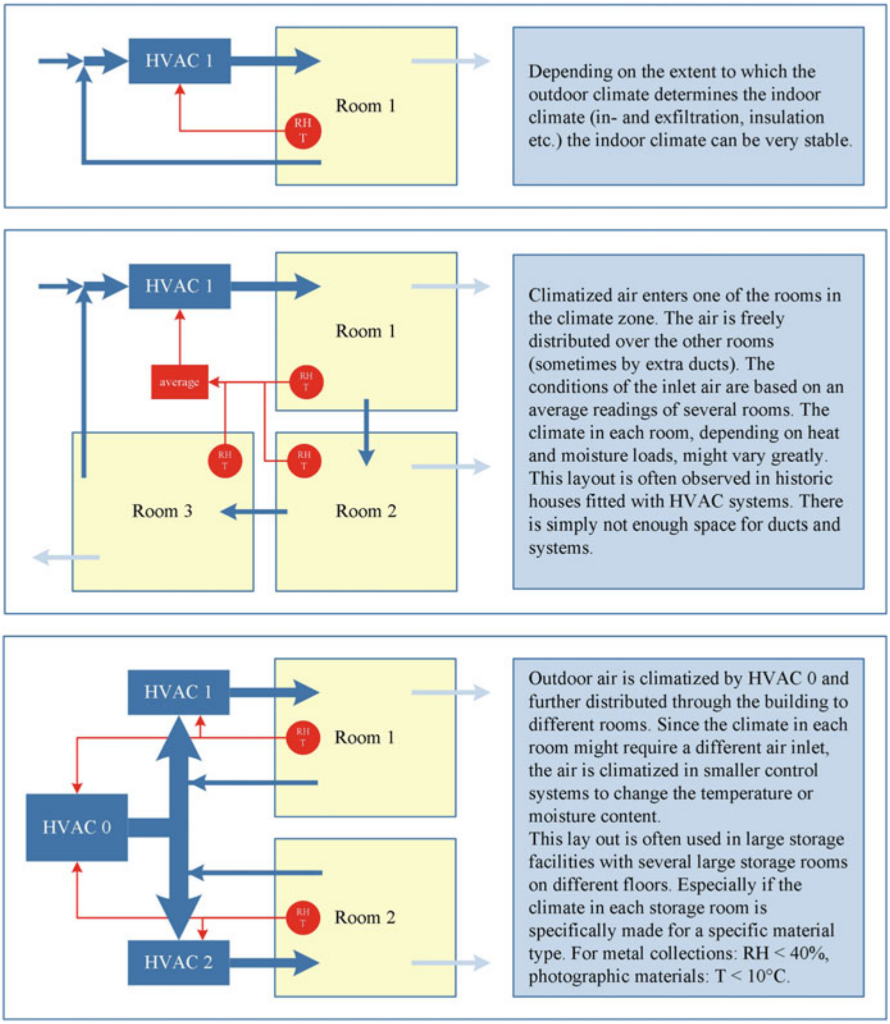

Fig. 9.16 Schematic presentation of the climate control strategy with one or more HVAC systems to control the indoor climate in one or more zones

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

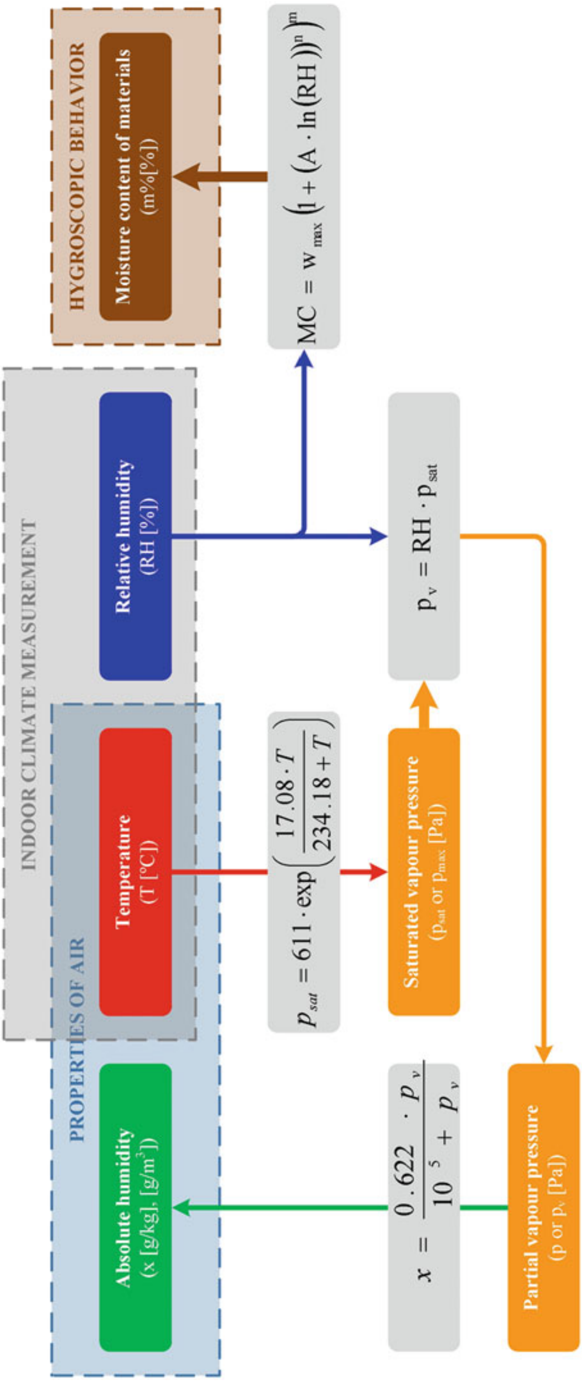

Fig. 9.18 The properties of air and their relationship with measurement and hygroscopic behavior of materials

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

[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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