Comparison of indoor climate analysis according to current climate guidelines with the conservational investigation using the example of Linderhof Palace

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Abstract

Linderhof Palace contains its original neo baroque furnishings, which consist of a large variety of composite materials. These artworks are affected by adverse indoor climate conditions such as cold temperatures and high relative humidity, which constantly fluctuates due to the high number of visitors. Depending on which guidelines are used, analysing and evaluating the indoor climate of a historic building can lead to different and sometimes opposing results concerning potential risks to the collection. The amplitude of fluctuations or the duration of a fluctuation affecting a certain kind of artwork are not considered in these guidelines. Some of the guidelines are based on the mechanical behaviour of objects, though only certain types of undamaged composite materials have been tested. Furthermore, it is unknown what risk of new damage is posed by deviating from the established environmental targets.

A detailed condition report on Linderhof's furnishings conducted 20 years ago was used to assess the present condition and to estimate the extent of changes induced by the climate over the last two decades. Different microclimates were identified, some of which had increased the rate of damage to the collection, such as flaking of gilded ornaments or painted wooden surfaces. The collection directly exposed to the external climate was particularly affected.

When these results were compared with an analysis of the indoor climate according to various recent guidelines it became apparent that many of the risks specific to each room at Linderhof were not covered by the usual statements of potential risk. Therefore, general climate guidelines are of limited use in estimating the potential for damage. In order to predict potential damage there is a pressing need to integrate knowledge about the characteristics of composite materials, their positions in the room and the possibility of the existence of distinct microclimates.

Linderhof Palace – more than a tourist attraction

Linderhof Palace, built by King Ludwig II is not only one of the most visited sites in Bavaria, it is also very interesting from a conservator's perspective. Most of the immovable furniture and fittings date to when Linderhof was built (1869–1885). The king's rooms on the upper floor are richly decorated with a large variety of materials (Figure 1), which respond in various ways to the indoor climate: painted ceilings, gilded stucco in the cavetto, oil paintings, gilded wooden ornaments on the walls and movable objects like tables and chairs, pastels, and textiles such as curtains, tapestries, and carpets, mainly produced by Bavarian artists. Little of the collection has been restored to date, with only a few repairs having been undertaken. Therefore all changes visible on the objects are related to the history and use of the building. The second point of interest is that the indoor climate of the palace is strongly affected by the location of the building (Figure 1, 2) and by the high numbers of visitors, particularly in the summer.

Climate in the Linderhof Palace

The climate in the Linderhof Palace is extreme all year round. Situated near the Alps, the outdoor climate is affected by long periods of frost and snow in the winter, as well as by rapid weather changes in the summer. The temperature span is therefore very wide. In 2010, outdoor temperatures ranging from -17.3 °C to 30.5 °C were measured. The relative humidity (RH) is constantly very high, in 2010 the average was 90.8 % [3].

Linderhof Palace has no air-conditioning system, so the indoor climate follows the outside climate, buffered to some extent by the building. Therefore sub-zero temperatures in the state rooms occur regularly. In February 2012, -6 °C and 64 % RH were measured in the king's bedroom, the coldest room in the building.

Daily fluctuations of temperature and relative humidity are especially frequent in the summer months. Due to the high number of visitors, the windows are kept open to ensure adequate ventilation. During any 24-hour period, fluctuations of 30 % RH from the hourly mean may occur.[1]

The indoor climates of each room in the palace differ substantially. Two rooms located at opposite ends of the palace were chosen to illustrate the differences. The Hall of Mirrors is south facing, and the Lilac Cabinet is at the northwest of the palace. Climate data were captured from loggers located in the middle of each room. The graph (Figure 4) shows data from 11 January 2011 to 10 January 2012. The differences in temperature, relative and absolute humidity between both rooms are illustrated by the grey line. In the Lilac Cabinet, the relative humidity was always higher than in the Hall of Mirrors, while the temperature was always lower. The rooms have a mean difference in relative humidity of 9.7 %, and a mean temperature difference of 2 K, but both have similar daily fluctuations as figure 3 shows.

[1] This is dependent on the method of analysing data. See this volume pages 439–450

[2] In this context, short term is taken to be daily

Figure 1. Linderhof Palace in 1887, by Ludwig Sailer [1]

Figure 2. Historic furnishings in the Hall of Mirrors, by Franz Hanfstaengl c. 1890 [2]

Major risks for climate-induced damage to the Linderhof Palace collection

A literature review was conducted to evaluate the risks posed to the interiors and collection by the indoor environment. This identified the most hazardous characteristics as excessive relative humidity in general, frequent daily and seasonal fluctuations, and very low temperatures in the winter.

Relative humidity above 70 %

The sorption isotherms of many organic materials, for example, animal glue, demonstrate a minor sorptive response between 40 and 60 % RH, but a high change in dimension and mechanical properties above 70 % RH [5].

Furthermore, the higher the relative humidity, the more drastic the hydrolytic cleavage of cellulose [6]. This causes long-term degradation in composite materials like paintings or wooden objects. Above 70 % RH, the risk of mould growth on artworks consisting of organic compounds is evident [7]. However, there are factors other than temperature and relative humidity which increase the risk of mould growth, such as substrate quality and the duration of coincidence. The American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) recommends maintaining an RH of below 75 % as the most basic level of environmental control, class D [8].

Fluctuation of relative humidity

Artworks consisting of organic materials swell and shrink with changes in relative humidity. Depending on the length and amplitude of the fluctuations, it is likely that there will be deterioration over time. The definition of an acceptable climate varies according to the author and the classification of the building in question. The ASHRAE standards dictate that fluctuations above 2.5 % per hour and 5 % per day are too high for a museum to be classified as AA standard [8, 9]. For historic buildings like the Linderhof Palace, Erhardt et al. assume, that short-term fluctuations[2] of 10 to 15 % above or below the monthly or annual average are still acceptable [6]. European Standard CEN/TC 346 recommends that the target range of indoor climate (when conditioned) should be within the 7th and 93rd percentile

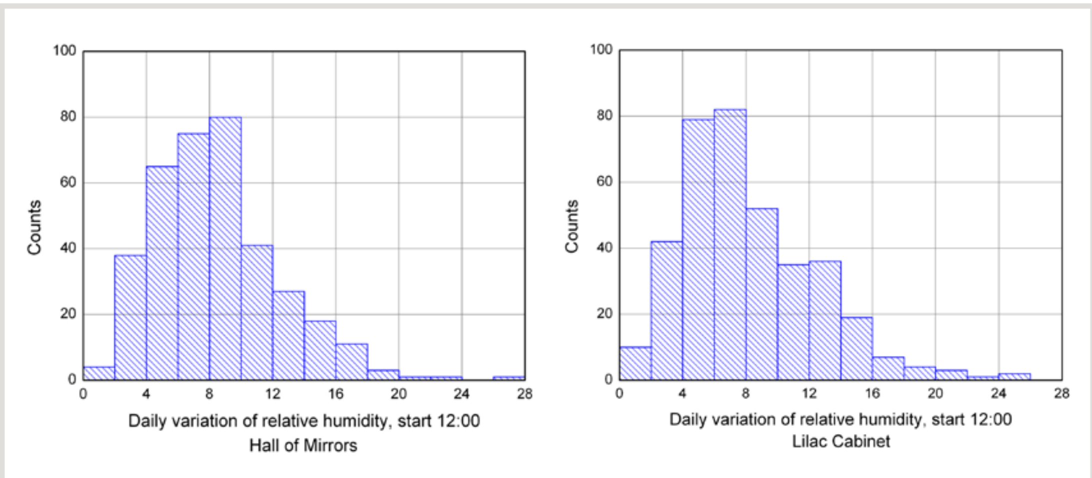

Figure 3. Histogram of the daily variation of relative humidity by the hourly mean. Left: Hall of Mirrors; Right: Lilac Cabinet. Both rooms show similar daily fluctuations of RH

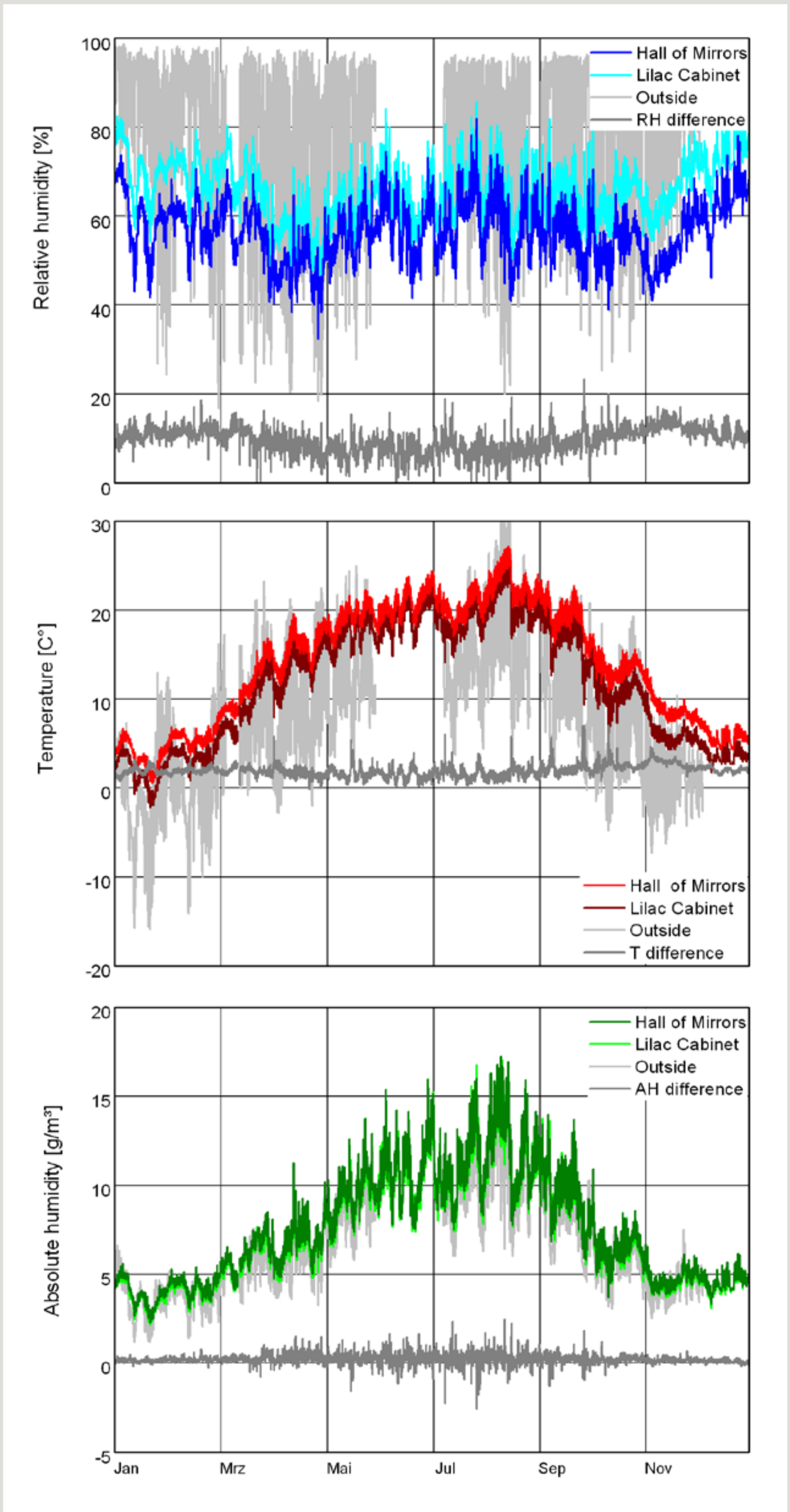

Figure 4. Line diagram of temperature, relative humidity and absolute humidity in the Hall of Mirrors and the Lilac Cabinet compared to the outside climate. Differences between both rooms are displayed in the dark grey line in each diagram

of measured values so that the driest and most humid extremes are avoided [10]. These guidelines mainly derive from theoretical approaches or from laboratory tests with un-aged materials combined with simulations.

Cold temperatures

Paintings, particularly in oil and acrylic, can be strongly affected by temperatures below zero due to their low glass transition

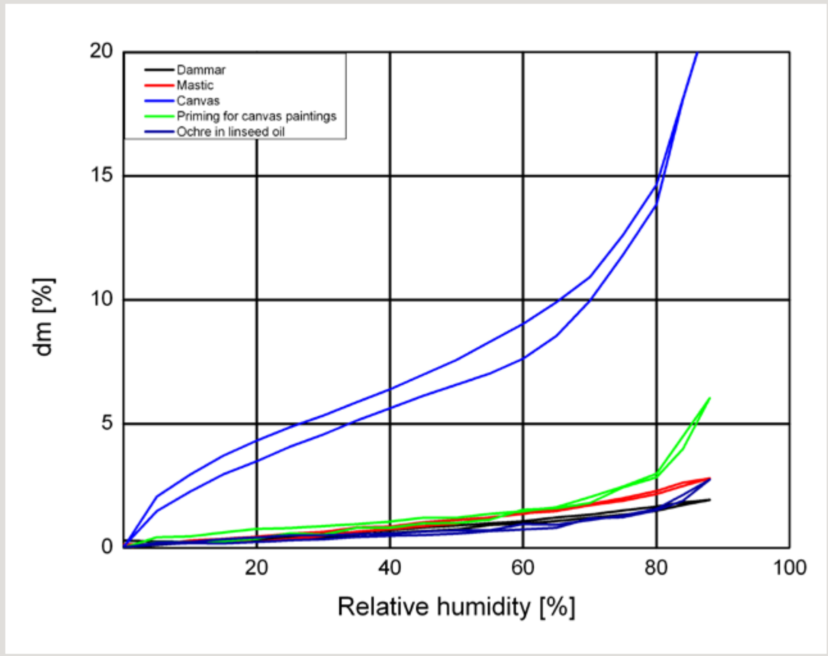

Figure 5. Diagram of sorption isotherms on organic materials: canvas, priming for canvas paintings, ochre in linseed oil, and dammar

temperatures. They can become brittle and flake. In this case, the effect of temperature is far more detrimental than the effect of relative humidity [11].

Evaluation of the indoor climate in the Linderhof Palace using different guidelines

In the following table, the three major risks related to the indoor climate in the Linderhof Palace are analysed according to various guidelines taken from the literature. Data from the Hall of Mirrors and the Lilac Cabinet reflecting the indoor climate for a period of one year were used. As the guidelines referring to average indoor climates do not usually take into account local microclimates, data from the surface measurement in the Lilac Cabinet were used for comparison. The percentage of data exceeding the limits recommended in the literature are listed below.

The table shows that climate data values for the Hall of Mirrors are in line with Thomson's recommended range as well as that of ASHRAE's control class D. Taking Thomson's guidelines for the Lilac Cabinet, however, the recommended range was exceeded by 27.8 % of the data recorded in the middle of the room and by 33.5 % on the surface. This is due to the higher relative humidity in the Lilac Cabinet. ASHRAE's control class D range was exceeded by 8.6 % of the data measured in the room and by 16.9 % of the data collected from the surface.

The data from all three locations fell beyond the recommended range established by deviation from the annual mean RH by plus or minus 10 to 15 %. Each location fell beyond the range by a similar amount. Assuming a 'moderate RH region' is around 50 to 55 %, the data falling beyond the plus/minus 10 to 15 % of this range increase for both measurement sites in the Lilac Cabinet: 50 % of the data on both measurement sites exceeded 55 plus or minus 10 % RH; 23 % in the middle of the room and 30 % on the surface position exceeded 55 plus or minus 15 % RH. The comparison of climate guidelines does not lead to a clear result. Interpreting the guidelines for relative humidity would imply that the historic interiors in the Hall of Mirrors should be in a better condition than in the Lilac Cabinet. Taking into account the data from the surface measurement it seems likely that more damage can be found on the collection situated near the outer walls. In terms of the low temperatures in the Palace, it is also likely that damage will be identified on artworks which have a low glass transition temperature as there are low temperatures in all rooms.

The impact of daily and seasonal fluctuations in temperature and relative humidity is not considered in sufficient depth by the guidelines, nor is there enough attention devoted to the varying responses of different classes of materials. Depending on their physical properties, materials react to environmental changes very differently. Structurally dense, composite objects such as gilded or coated wood are much less responsive to climatic changes than more permeable materials, as the movement of moisture through the structure takes so much longer. The thickness of the various layers of material is also a major factor.

It is vital to distinguish the particular material or composite materials to which these guidelines refer. For example, painted or gilded wooden objects are damaged severely by seasonal environmental fluctuations, which can cause cracking in the wood [13], while very sensitive materials like parchment react immediately and visibly to very short fluctuations of relative humidity.

In summary, it is necessary to verify the estimates of risk implied by the data by investigating the actual condition of objects and interiors:

- What is the condition of various objects of different composite materials installed in the palace?

Table 1. Indoor climate data from the Hall of Mirrors (air) and the Lilac Cabinet (air and surface) analysed by different guidelines taken from literature

Literature	Description	Hall of Mirrors – sensor in the middle of the room	Lilac Cabinet – sensor in the middle of the room	Lilac Cabinet – sensor on the outside wall
		Data exceeding the limit	Data exceeding the limit	Data exceeding the limit
Thomson [12]	40 to 70 % RH	1.8 %	27.8 %	33.5 %
ASHRAE, class of control D [8]	Data should stay below 75 % RH	0.1 %	8.6 %	16.9 %
Erhardt et al. [6] ASHRAE class of control B [8]	"Changes caused by environmental fluctuations ± 10–15 in the moderate RH region are generally reversible"	Annual mean 56 % ± 10 % = 46–66 % RH: 12.6 %	Annual mean 66 % ± 10 % = 56–76 % RH: 6.9 %	Annual mean 67 % ± 10 % = 57–77 % RH: 11.5 %
Erhardt et al. [6]	"Changes caused by environmental fluctuations ± 10–15 in the moderate RH region are generally reversible"	Annual mean 56 % ± 15 % = 41–71 % RH: 1.2 %	Annual mean 66 % ± 15% = 51–81 % RH: 2 %	Annual mean 67 % ± 15 % = 52–82 % RH: 1.4 %
Mecklenburg [11]	Temperature below 0 resp. 8 °C	< 0 °C: 0 % < 8 °C: 26.5 %	< 0 °C: 1.4 % < 8 °C: 35.5 %	< 0 °C: 2.4 % < 8 °C: 15.8 %

- Does the condition of furnishing and objects vary in different rooms?
- Does the location of the furnishing or object in the room influence condition?

Method of investigation of the state of preservation

Condition photographs were compared in order to evaluate deterioration and damage during recent years. A photographic condition survey of all immovable furnishings was undertaken in 1992. Certain types of damage were identified in this survey. For example, flaking and cracks in gilded surfaces, which indicate climate-related deterioration, as well as water marks caused by historic water leaks or surfaces which had been abraded due to touching by visitors. This type of damage was described and photographs of particular examples were taken in every room. These images allowed the condition of the collection in the 1990s to be compared with the present condition. Oil paintings and gilded surfaces were selected for particular investigation as these were best documented. Due to the risk of mould growth at high relative humidities, particular care was taken to examine corners with little air exchange or air flow.

The gilded ornaments were composed of wooden supports, glue layers, priming, bolus, covered with gold leaf and a coating. Only the gilded wooden decoration on the walls in the bedroom was created with a different technique, here the wooden support had very thin priming and the gold leaf was fixed with an oily binding media.[3] The oil paintings had a thin priming, with a thin occasionally opaque paint layer, covered with a varnish.

Results of the in situ investigation

Different observations can be made about the various materials examined. Fragile objects, for example pastels and textiles, were greatly affected by the climate. Materials insensitive to environmental changes, such as porcelain vases, were in a very good state of preservation. Furnishings located in the middle of the room had not changed significantly during the last two decades. Damage like loss of gilded surfaces were already visible on the pictures from 1992 (Figure 6).

The greater fluctuation in relative humidity caused by the use of the historic heating system when the king was attendant might be one of the causes of the pre-existing damage.[4]

The cardinal direction of the room did not appear to influence condition. However, the surface condition of wooden gilded objects on the walls in the bedroom varied according to production technique.

The biggest changes in condition were observed in gilded wooden decorations installed near to or on outer walls (Figure 7). Most notably the folding shutters, decorated with gilded sand-textured surfaces and wood carved ornaments, presented heavy losses and loosening. Paintings on canvas hanging on outer walls, as in the audience chamber, were heavily warped as a result of their exposure to severe environmental fluctuations. Only few craquelures were visible.

[3] The bedroom has been adapted by Ludwig II and was not finished before his death. This was realized only after the palace was opened to the public

[4] Historic documents describe early repairs to the historic furnishing, for example cracked pieces of lapis lazuli on the fireside in the Hall of Mirrors

[5] In winter 2012 three samples were taken to see if the mould growth identified was active. The analysis showed that no active infestation could be observed at that time.

Mould growth[5] was found in many areas, particularly in corners where the air exchange was very low, such as in folded shutters and the state bed (Figure 8). Separated from the visitors by a balustrade, the wooden gilded bed, furnished with a coating made of glue, presents an ideal medium for fungi. In some areas the painted wooden surfaces, which have been painted over with an acrylic medium, are flaking probably due to temperatures below the glass transition temperature of the binder.

Combining the results from the in situ investigation with the estimates from the climate data analysed, it is possible to conclude that, in general, the prediction of little damage for the historic furnishing situated in the middle of the room was broadly correct. More in depth predictions, specific to particular composite materials, could not be made. It was not possible to confirm differences in the condition of the same types of furnishings located in different rooms. Surprisingly, the condition of the gilded surfaces on the walls in the bedroom, the room with the highest RH and the coldest temperatures, was very good. This confirms that the particular gilding technique, which was different from the other rooms, is a major influence in the preservation.

Conclusion and outlook

This comparison of predictions drawn from an analysis of environmental data with a conservation condition survey has demonstrated that the predictions derived from the climate data alone are limited. The results of the environmental data analysis differ according to the particular guidelines used, which undermines the efficacy of such an approach. A room never has one single climate, and there is most potential for damage in extreme local microclimates. When predicting future damage, it

Figure 6. Audience room, east wall, gilded ornaments on the baldachin: losses and loosening of the gilded surfaces have not increased during the last 20 years

Figure 7. Yellow Cabinet, western wall, heavy losses to the silvered ornaments

Figure 8. Mould growth on the gilded state bed in the King's bedroom

is also necessary to take into account the specific characteristics of different composite materials. Last but not least, there is a considerable lack of knowledge about the risk of new damage posed by long-term deviation from the environmental guidelines. Fluctuations are not the only risk historic furnishings are exposed to. Light and pollutants have a major influence. In historic interiors it is not always easy to distinguish between single influences, and it is likely that there will be some deterioration factors which are interlinked and mutually dependent.

Linderhof was an attempt to compare guidelines derived from analysed climate data with results from a conservation condition survey. More buildings should be investigated to produce more reliable predictions and results. In order to better understand the risks posed by environmental fluctuations to collections in real conditions, further investigations are necessary into material characteristics, for example, simulations of hygrothermal processes on different artworks and in situ measurements with infrared thermography or 3D digitizing investigations.

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Image credits

Figure 6 left: 1992 Kriewitz/Mayrhofer, right: 2012 Holl/Raffler
Figure 7 left: 1992 Kriewitz/Mayrhofer, right: 2012 Holl/Raffler
Figure 8. 2012 Holl/Raffler

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