# Concept of a New Airing Strategy and Simulation of the Expected Indoor Climate in Linderhof Palace

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**Abstract**

*This paper is part of a research project of Fraunhofer-Institute for Building Physics IBP at Holzkirchen for preventive conservation of cultural heritage which has been conducted in close cooperation with the Bavarian State Administration of Castles, Lakes and Gardens (BSV). Within this research project the influences on and the behavior of the room climate in Linderhof palace of the Bavarian King Ludwig II. have been investigated. The room climate is very important for the long-term preservation of art. Based on an already done building simulation of the king´s bedchamber in previous work, this paper highlights a newly developed airing concept for Linderhof palace. Alternative airing strategies are investigated computationally and discussed regarding to climatic stability and energy consumption. The existing airing concept of the natural ventilated and nowadays completely unheated Linderhof palace has to be improved to reduce proceeding damage to artworks due to fluctuations of the inner climate caused by the ambient climate and visitors, and also to enhance the visitors comfort. In a valuable historic palace building there are specific restrictions for applying a typical HVAC system: Possible damage to artworks and building materials from condensation effects, high energy consumption and the need for an invisible, minimal invasive installation of technical devices. According to the agreement with the Bavarian state department for palaces, gardens and lakes the historic chimneys may be re-used for climatization. The new airing concept considers new and on-going discussed strategies of acceptable humidity ranges for the preservation of art. For low energy consumption only drying of the ambient air is considered in a cooling process with heat recovering. No humidification is foreseen in the air handling process. Heating of the supply air is planned only for very low temperature and in danger of dew-point. This concept is simulated with an existing WUFI® Plus building simulation model of the king´s bedchamber. First results are promising to accomplish all of the wanted objectives. A pilot HVAC system is recommended, based on the results shown, and foreseen in a follow-up project with the Bavarian state department for Castles, Gardens and Lakes (BSV).*

***Linderhof palace, whole building simulation, Influence of visitors, preventive conservation, HVAC in historic buildings***

## 1. Introduction

In the years 2008 to 2011 the behavior of the room climate in Linderhof Palace (Figure 1) of the Bavarian King Ludwig II has been investigated by long term measurements to assess the influence on preservation. For a one year´s period building simulation was done with focus on one room with especially interesting indoor conditions and building characteristics, the King´s bedchamber. In order to get a deeper understanding for the way of implementation of the simulation model, a short overview is given on building history and a more detailed view on the construction and also on the room climate of this unheated historic building, with a special focus on the King's bedroom. The translation of the building construction and adjacent room climates as boundary conditions to the simulation model are shown in detail. The indoor environment is very important for the preservation of art. Especially high fluctuations in relative humidity are of interest, because they can cause damages to the building construction and to art works. Therefore relative humidity deserves a special focus.

Due to 3000 and sometimes more visitor per day in summertime a special view will be given on the influence of the visitors to the room climate condition. To be able to distinguish between influence of visitors and influence of ambient climate through ventilation a well fitted simulation model is necessary.

Figure 1: The left picture shows the front view with entrance of Linderhof Palace. The right picture shows the rear view of the palace. The middle building section of the the right picture shows the three big windows of the bedchamber. (Source: BSV).

## 2. Building

### Building History and Interior Design

Linderhof palace was mainly built up from 1868 to 1876 by the Bavarian King Ludwig II. in the Graswang valley surrounded by the Bavarian Alps. The forested park, where the castle is located, is about 940 m above sea level between mountain ridges rising up to 2185 m high. The valley is west-east oriented. The last building phase was in 1886 with enlarging the king´s bedchamber. Only some weeks after death of the King the bedchamber has been finished and the palace has been opened to the public. Since this time the palace stayed unheated. The interior of the upper floor, where the show rooms are, is richly furnished. Figure 2 shows views of the king´s bedchamber. Almost every piece of the interior is a work of art.

Figure 2: The pictures show the bedchamber, the biggest room in the castle with a volume of ca. 805 m³. In the middle of the left picture the royal bed can be seen. The visitors cross the room in front of the balustrade. The right picture shows the north wall with the three big windows without curtains. (BSV).

## Building Components

The outer and inner walls of the building are made of bricks. In every room a special construction made of wooden panels is assembled on the wall with a certain distance of a few centimeters to the wall. Gilded carvings, paintings and decorations are fixed on these wooden panels. The windows in the palace are still the original wooden single glazed windows. The joinery work is well performed, all joints are closed and gaps are narrow. All windows in the ground floor are always closed. The windows in the upper floor with the representative rooms are also all single framed. Only in the bedchamber there are boxed windows with two single glazed frames. Every day when the palace is shut down additional inner shutters on the windows are closed. This improves the air tightness of the windows considerably. A construction detail of the outer wall and window of the red marked bedchamber is shown in Figure 3. This component is also shown in Figure 6 with assembly within the building simulation software WUFI® plus.

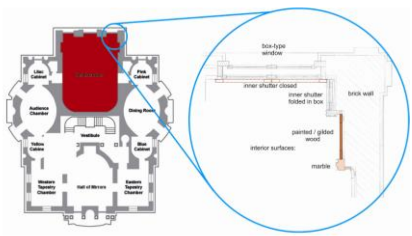


Figure 3: Detail of wall construction with interior surface consisting mainly of framed gilded or painted wood. The opened inner shutter is hidden in a lateral box.

### Visitors and Ventilation of the Building

Most visitors come in summer time. Opening hours in summer period are from 8.00 AM to 6 PM. From December 2009 to December 2010 overall approximately 450.000 visitors stayed in Linderhof. The building is open almost every day (except for 5 days) of the year. In Figure 5 the visitor's route is explained graphically. There are five stations on the tour where explanations are given through the guides. The route follows in the upper floor in clockwise direction, see green arrows in Figure 4. During opening hours the windows are opened by the tour guides. If the weather is not too bad the guides open the windows as required. This means during summer almost all windows are open during opening hours in the upper floor, where the showrooms are. Only in the bedchamber the windows are always closed. The blue arrows in Figure 5 show the windows which are used for ventilation.

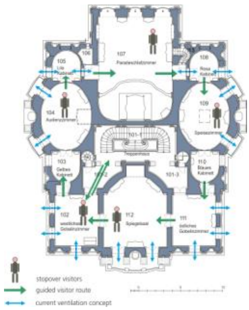


Figure 4: Upper floor with visitor´s route clockwise through the show rooms (green arrows). The blue arrows show the windows used by tour guides for airing. The windows in the bedchamber are never opened for airing. (Plan material: BSV).

## 3. Measured Climates

First measurements have started in February 2008. Here, a one year period from 1st Dec 2009 to 1st Dec 2010 is analyzed further. A one year period consists of 8760 hours. Due to failures in data recording some data are missing. This has to be considered when interpreting the statistical figures.

### RH of Ambient and Room Climate of King´s Bedchamber

With 90.8 % RH the relative humidity of the ambient climate is in average very high. This may be due to special conditions of the mountain valley. The relative humidity goes up and down in daily cycles, especially in the warm summer period, decreasing to 24 % RH. For the RH in the bedchamber a seasonal cycle can be observed with a monthly moving average (MA) of the hourly data between 80% RH in winter and 60 % RH in summer.

### Temperature of Ambient and Room Climate of King´s Bedchamber

The average ambient temperature in this year period is 5.4 °C with a maximum of 30.5 °C and a minimum of -17.3 °C. The monthly moving average (MA) shows a maximum of 15.1 °C in summer and minimum in winter with -5.6 °C. In comparison the indoor climate has an average temperature lift of 5.9 Kelvin up to a year´s average temperature of 11.4 °C. In summer the indoors maximum is at 26.5 °C and the minimum in winter at -1.5 °C.

### Fluctuation of Relative Humidity

The fluctuation of the relative humidity is important for the preservation of works of art. There are several definitions of acceptable ranges of RH. For example ASHRAE [1] gives a definition for different climate ranges of museums and archives. For historic and listed buildings, also churches, different definitions for acceptable climates are given. For the purpose of this paper detailed definitions are not necessary, but it becomes important as a measure for the quality of the improvement of indoor climate, since climate fluctuations are important for preservation of Artwork. A common value is the daily fluctuation. For each day the maximum and minimum RH are compared. The difference gives the maximum fluctuation (or range) for each day. The new approach presented here does not consider the maximum difference for one day, but a moving 24 hour interval. That means every hour a 24 hour interval is inspected for the maximum fluctuation range. With this method a more sophisticated investigation of fluctuations can be made compared to an equidistant method. For the purpose of this paper the comparison of the moving fluctuation is used as a measure for the quality of the simulation.

### Adjacent Climates

In total there are twelve adjacent climates to the king´s bedchamber as further boundary conditions. These climates are indoor climates of adjacent rooms in the same floor, rooms underneath and above, cavities and void rooms and the ambient climate. There are also cavities and voids with own climates. All these climates were measured and used as boundary conditions.

## 4. Building Simulation Model

The calculation software WUFI® plus is based on the coupling of several one-dimensional calculations of the building components and their respective areas [5, 7]. Within this software tool it is possible to calculate temperature and relative humidity of the indoor climate of the king´s bedchamber. After calibrating and some validation [4] it is possible to simulate the scenario of indoor climate with a HVAC application.

## Simulation Model

All different building components are transferred from the plans and in situ measurements to the simulation software and implemented in a building model. The single building assemblies and climates are assigned to each single area in the software model, see Figure 5.

Figure 6 shows the computer model and the construction assembly in the north eastern corner of the bedroom (see also Figure 3). Inside and outside climates are shown in different colors (white or light yellow) in the 3D model. The ceiling to the attic is e.g. red marked on the upper side. The visible door openings are the passages to the adjacent rooms, called cabinets. The windows are shown as light blue transparent surfaces. The non-filled areas adjacent to the bedroom set the outlines of the castle.

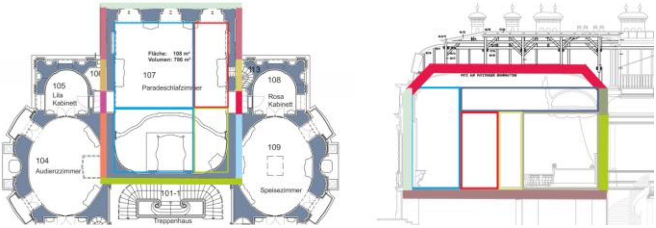


Figure 5: Upper floor plan with a sketch of the simplified room model of the King’s Bedchamber with different wall partitions and their referred climate. The rectangle areas show rooms below in the ground floor with their arrangement in the building simulation. The right picture shows the model in cross-section lengthwise with referred building assembly and adjacent climate zones. (Plan Material: BSV)

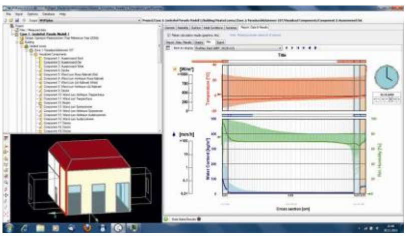

Figure 6: Screenshot of WUFI® plus simulation model of the King´s Bedchamber. A calculation run is shown of the building component “outer wall” as depicted in figure 4. The assembly of this component is shown on the right with outer plaster, wall brick, air layer and inner wood cladding. The red layer shows the calculated band on temperature within the building component the red line shows the actual calculated temperature at the specific time step, the green layer shows the band of relative humidity and blue shows the water content.

## Profiles of Inner Sources

The profile of inner sources for heat, moisture and carbon dioxide is derived mainly from the visitor profile. There is a strong seasonal cycle of visitor numbers. During winter there are only 299 visitors per day in average, down to 50 people and less on some days. In contrast in summertime there are 2391 visitors per day in average, up to 3500 people and more on some days. The numbers of visitors were derived from the daily number of entrance cards for the examined year. Visitors contribute with moisture, temperature and $CO_2$-emissions to the indoor environment. For a detailed emission profile of the visitors the actual length of stay of people in the bedchamber is needed. A measurement on a typical summer day gave an average stay of 4.7 minutes per visitors in the room. If we calculate 4.7 minutes/visitor divided by 60 minutes per hour we get an equivalent stay of a hypothetical visitor for one hour. For example in months with an average of 2391 visitors per day we get approximately 187 equivalent visitors staying during opening time in the bedchamber.

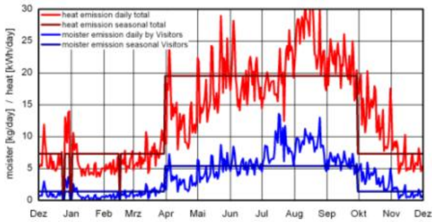


Figure 7: Detailed hourly profiles of equivalent staying visitors for heat and vapor emission in the bedchamber. Additionally the seasonal average profiles are shown.

With this daily visitor profile, using common available figures for temperature depending human emissions (e.g. VDI 2078) and daily opening times we can calculate a detailed hourly visitor profile. Figure 7 shows the profiles for heat emission with additional heating through electric lighting and a profile of water vapor emission. Over all for one year we get a heat emission due to visitors of circa 3531 kWh and a moisture emission of ca. 1236 kg water only for the bedchamber.

## 5. Building Simulation Scenario with HVAC

### HVAC Solution

The newly developed HVAC solution has been derived respecting the goals from preventive conservation and the need for a low impact of a HVAC solution to the building construction and energy consumption.

There exist many aspects that have to be considered in regard to preventive conservation. In this paper only temperature as well as fluctuations and level of relative humidity are highlighted. The existing climate should not be changed too much. The aim of the climatization concept is to just reduce the overall level of fluctuations and to reduce high moisture events. An example for improving indoor climates in this way is given in [9]. This implicates no or only little heating. If there is no (or little) heating only limited air moistening is necessary in winter time. The palace should stay basically unheated. This decision saves obviously energy compared to a full HVAC solution with constant temperature.

This requirement derives also from avoiding strong changes in long term equilibrium moisture content (EMC) of the interior materials. The same consequence derives from avoiding damaging events from technical malfunction. If a new climate corridor would be established even carefully, a malfunction of the HVAC would result in the former climate corridor. This would cause a major change to the EMC of art materials and could possibly cause damages of the interior. If we stick to the old climate corridor in seasonal gliding of temperature and a fairly constant height of RH the palace administration could benefit by being secure also of possible impacts of HVAC breakdown. Currently the level of RH is slightly too high, especially during the winter half year´s period. A new airing concept should bring down the moisture level only slightly, just to a more secure level regarding mold risk. A level above 75 % RH is seen as critical and should be avoided.

## Building Simulation with HVAC Solution

The simulation parameters were set to an air change rate of a constant value of 0.13 $h^{-1}$ plus an additional air volume of 15 $m^3$ per equivalent visitor. To supply the room with fresh air only a fan is necessary. To enable more climate control an option for dehumidification is foreseen and also for heating. Heating up the air will lower the RH. This phenomenon is known as conservation heating concept, and sometimes used in historic buildings to control RH. This concept is implemented in the simulation only in a limited way. The heating will start only if the indoor climate exceeds 70 % RH. The maximum heating power is also limited to 5 kW, and operating time of the implemented HVAC simulation solution is only during opening time because of a fire protection order to shut down the electric circuit during closing time.

It is assumed that dehumidification is more efficient compared to heating in case of Linderhof palace. The dehumidification is implemented in the simulation as a preset value of RH level of ambient climate. This means the air intake of ambient air is dried down to 70 % RH at unchanged temperature level of ambient air. Additional to the HVAC scenario, the real indoor climate of the king´s bedchamber is calculated and compared. Due to measurement failures there are missing data in boundary conditions. These time periods are omitted in the calculation result shown in the graphs in figure 8 and 9. Comparing both simulations, with the HVAC solution a more stable long term climate can be observed, with a slightly lower level of RH. This results in a more stable EMC of the materials. The annual average in RH drops marginally from 67 % RH to 65 % RH. A closer look to the RH short term fluctuations is shown in figure 9. The simulated HVAC solution improves also the short term fluctuations.

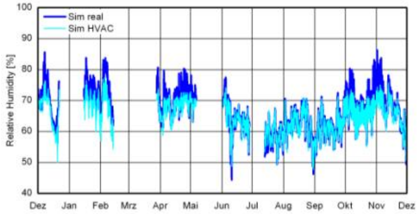


Figure 8: The dark blue line shows the simulated real indoor climate. The light blue line shows the result of the scenario with an HVAC solution. The time period is from Dec 2009 to Dec 2010. The periods with incomplete boundary conditions are omitted.

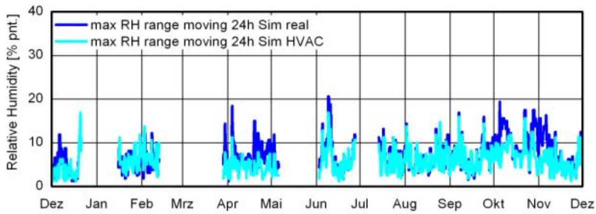


Figure 9: Comparing the short term fluctuations of the two simulations shows with the light blue line a slightly improved RH range in case of the simulated HVAC solution (light blue). The time period is from Dec 2009 to Dec 2010. The periods with uncomplete boundary conditions are omitted.

### Energy Consumption

The energy input in this system is calculated for one year without omitted periods. Two ways of energy input is implemented with drying of the ambient air to a level of 70 % RH and additional heating of the incoming ambient air if the indoor air exceeds 70 % RH. In the simulation this is calculated by changes in enthalpy of ambient air and heating input. The calculated energy input is about 257 kWh in this example for one year during opening time. This means in average an electric power of about 75 Watt during opening time. The calculation of energy consumption does not take into account the real performance of a technical unit.

## 6. A New Airing Concept for Linderhof Palace

Beside an efficient HVAC solution with an improvement to the indoor climate, it is crucial to be able to install an HVAC system with low impact to the original building construction to the listed building Linderhof palace with its extraordinary interior. An investigation made by the Bavarian State Administration of Castles shows possibilities to use the old air heating system and existing chimneys for air ducts. Figure 10 shows one possible concept for airing the main part of the upper floor with the part of the palace with most problems in RH level. The new air inlet is planned to be installed in an open constructed chimney. The chimney was already historically used as air inlet for warm air, heated by a wood fired oven in the rooms below. Fortunately it is possible to install a HVAC solution below the king´s bedroom in a cellar room with no historical surfaces. Since there are a lot of visitors in the palace during opening time, it is foreseen in this concept to use displacement ventilation. Figure 11 shows the air inlet in the king´s bedroom at the right chimney. A possible option is to use the left chimney too. To get air currents in both wings of the palace and finally outside, two chimneys will be used for air outlet. Fans are foreseen in both chimneys to control the air flow by pressure difference. Typically for displacement would be an air outlet in the upper region of the room. This is not possible in case of Linderhof.

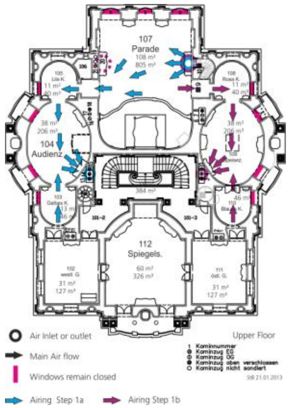


Figure 10: Ventilation concept of Linderhof Palace for the main part in the upper floor. Displacement ventilation with air inlet in the king´s bedchamber and controlled air outlet in the Audience chamber and Dining room.

## 7. Conclusions and Outlook

Linderhof Palace is a touristic magnet, especially in summer time. Beside ambient climate there is an essential influence of the visitors on the indoor climate. The traditional airing concept with opening windows has many disadvantages like pest infestation, dust, mechanic damages by use and so on. For preventive conservation closed windows are beneficial in many ways. This is only possible with mechanical ventilation.

With a rough implementation of the building and the boundary conditions a fairly good correspondence to measured data may be reached by hygrothermal whole building simulation. With the introduced airing concept and simulation of the concepts we are able to study the possible impacts on indoor climate and energy consumption. The introduced results show possibilities to improve the indoor climate for conservation by controlled ventilation with closed windows and at the same time with low energy demand. An important prerequisite is to investigate possible solutions for implementing HVAC and ventilation devices as it is shown. Further investigations are necessary to get a more thorough understanding on impacts of variations of HVAC solutions in historic buildings. Next steps are investigations on preconditioning of air with underground air ducts of ambient air and improvement of the simulation on multizonal airflow.

## 8. Acknowledgements

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