ROOM CLIMATE IN LINDERHOF PALACE
Impact of ambient climate and visitors on room climate with a special focus on the bedchamber of King Ludwig II.

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Abstract: This report is part of the European research project "Climate for Culture" of the Fraunhofer Institute for Building Physics IBP at Holzkirchen on preventive conservation of cultural heritage. Within this project the influence and behaviour of the room climate in Linderhof palace of the Bavarian King Ludwig II. will be investigated by measurement and building simulation. The outer climate, the impact on the room climate of the King's Bedroom and the room climate itself will be introduced. To get a better understanding of the impact of the outer climate to the room climate a short overview is given to building history and construction of the unheated historic building. The room climate is very important for the preservation of art. Especially high fluctuations in relative humidity are of interest, as they can cause damages. Up to 3000 and more visitors are coming to Linderhof palace (Figure 1) per day in summertime. Therefore a special view on visitors comfort will be given due to room climate conditions.

Keywords: structure component, room climate, cultural heritage, preventive conservation

1. INTRODUCTION

In the years 2008 to 2011 the influence and behaviour of the room climate in Linderhof palace of the Bavarian King Ludwig II has been investigated by measurement and building simulation with a special focus on the connection between the outer climate, the room climate and other influences, like visitors. A short overview is given to building history and construction of the unheated historic building, with a special focus on the room climate of the King's Bedroom. The room climate is very important for the preservation of art. Especially high fluctuations in relative humidity are of interest, as they can cause damages. Up to 3000 and more visitors are coming to Linderhof palace (Figure 1) per day in summertime. Therefore a special view on visitors comfort will be given due to room climate conditions.

Figure 1 The picture shows the front view with entrance of Linderhof Palace. (Source: Bayerische Schlösserverwaltung BSV).

2. BUILDING

2.1. Building history

Linderhof palace was mainly build up from 1868 to 1876 from the Bavarian King Ludwig II. in the Bavarian alps in Graswang Valley. The forested park where the castle is located is about 940 m above sea level between mountain ridges up to 2185 high. The valley is west-east oriented. The last building phase was built in 1886 with enlarging the king´s bedchamber. Some weeks after death of the King the bedchamber has been accomplished and opened to the public. Since this time the palace has been stayed unheated. In Figure 2 the different building phases are coloured illustrated.

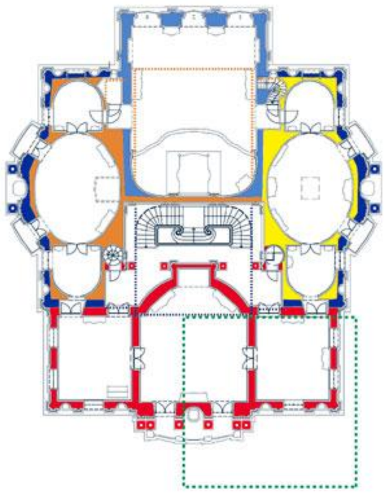

Figure 2 Upper floor of Linderhof palace with six building phases. The King´s bedchamber is the biggest room and was accomplished in the very last building phase after death of King Ludwig II in 1886 (light blue room). (Source: BSV).

2.2. Building components

The outer and inner walls of the building are made of bricks. On the inner side in every room a special construction made of wooden panels is assembled on the wall with a certain distance of a few centimetres 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 of the construction period. All of them are in a good condition. 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 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 may improve the air tightness of the windows considerably. A construction detail of the outer wall and window of the bedchamber is shown in Figure 3.

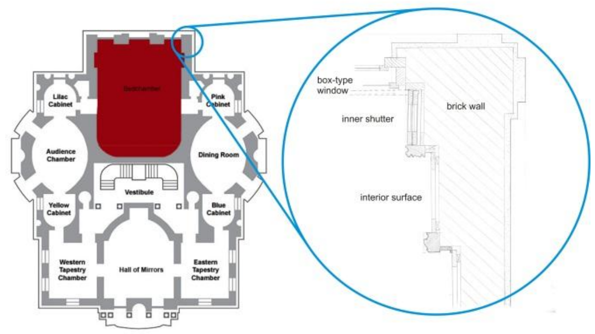

Figure 3 Detail of wall construction with interior surface consisting mainly of framed wood gilded or painted. The opened inner shutter is hidden in a lateral box.

2.3. Ventilation of the Building

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 palace is opened in summer period from 7.00 a.m. starting ventilation with opening of all windows in the upper floor due to odour and cleaning until 8.00 a.m. The guided tours lead only to the upper floor and the royal rooms with rich furnishing on interior surface. The king´s bedchamber is partly shown in Figure 4.

3. GENERAL VIEW ON AMBIENT CLIMATE

First measurements have started in February 2008. Here, the one year period from 21.06.2009 to 20.06.2010 will be introduced and analysed. A one year period consists of 8760 hours. In this period 8586 data out of 8760 had been recorded. This is to consider in interpreting the statistical figures. The data have been measured in a 5-minute interval. The hourly data is the mean value of every 5-minute measured data of one hour. The sensors for relative humidity and temperature are placed on the north side of the castle on a balcony. Additional measurements have been made at the "Grotte", about some hundred meters in distance to the castle. Due to partly faults in measurement the data have been combined.

Figure 4 The pictures show the bedchamber, the biggest room in the castle with a volume of ca. 805 m³. In the middle of the upper picture the royal bed can be seen. The visitors cross the room in front of the balustrade. The lower picture shows the windows without curtains and on the right the window and wall corner details shown in figure 3.

Relative Humidity of ambient climate

The relative humidity is in average very high with 95.1 % RH. This may be due to special conditions of the mountain valley. The relative humidity goes down in daily cycles, especially in the warm summer period, up to 24 % RH. A weak seasonal cycle can be observed with a monthly moving average (MA) of the hourly data, depicted in Figure 5.

Temperature of ambient climate

Figure 6 shows the ambient temperature with seasonal cycle. The average temperature in this year period is 5.46 °C with a maximum of 29.2 degree and a minimum of -17.3. The monthly moving average (MA) gives damped figures with maximum of 15.1 °C in summer (05.08.2009) and minimum in winter (17.01.2010) with -5.6 °C. Based on this data a sine function can be calculated, describing the idealized seasonal cycle:

$$T(x) = 5.50 - 10.322 * sin(((2*\pi)/365) * (x-35)) \qquad (1)$$

Where T is temperature and x denotes time in days from the beginning of year.

Absolute Humidity of ambient climate

Absolute humidity has to be calculated from temperature and relative humidity. This parameter gives the water content per m³ air. This becomes important for comparing ambient water content and water content of inside air of the castle. In average there is 7.25 gram water per m³ air enclosed. A maximum is given of 16.5 g/m³ without a peak in June which is probably a measurement fault. The hourly measured minimum water content is in winter with 1.13 g/m³. The monthly moving average (MA) is in maximum 12.51 g/m³ and minimum 3.13 g/m³, see Figure 7.

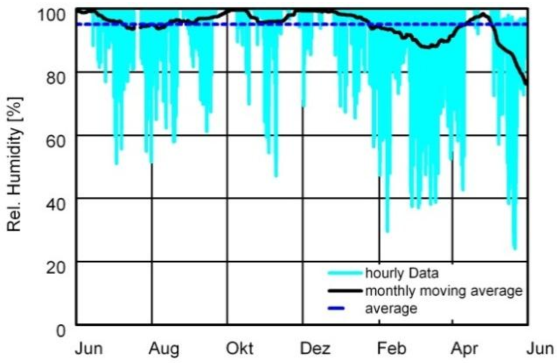

Figure 5 Relative humidity of ambient climate with monthly moving average and average of whole period, from 06/2009 until 06/2010.

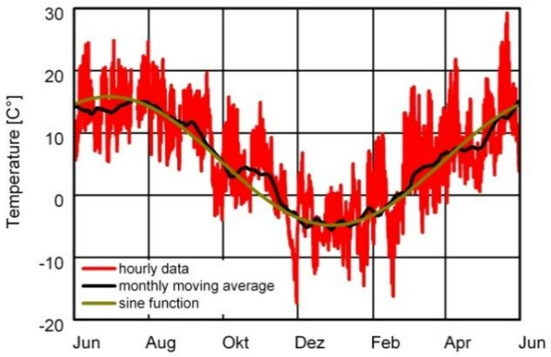

Figure 6 Ambient climate temperature with monthly moving average and sine function, from 06/2009 until 06/2010.

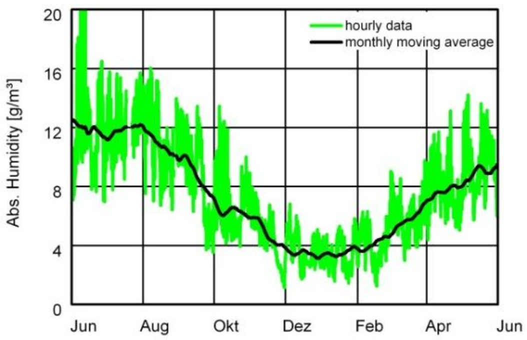

Figure 7 Absolute humidity of ambient climate with monthly moving average, from 06/2009 until 06/2010.

4. ROOM CLIMATE OF KING´S BEDCHAMBER

The data consists of 8181 hourly values (from 8760 hours of a year), obtained as a mean value from 5-minute measured data. In the bedchamber two sensors for relative humidity are placed to secure the measurements. The accuracy of these sensors is ± 0.3 Kelvin and ± 3 % point relative humidity. The used sensor types are sensors transforming the analogue signal in a digital signal, type SHT 15 and HIH 4000.

4.1. Relative Humidity

The average for this year period is 72.4 % RH which is on very high level. Figure 8 shows the course of the graph. In June 2010 there can be observed some downward trend. This trend turns in July (not shown). There is a maximum of 96 % RH and a minimum of 46 % RH. The seasonal cycle of the RH of the bedchamber is in maximum in monthly moving average (MA) 80.1 % RH and minimum 63.8 % RH (without figures in June 2010). The annual monthly moving average cycle of RH in the bedchamber follows the RH cycle of the ambient climate. This is also due to the annual temperature cycle. Mean difference in RH between bedchamber climate and ambient climate is 22.7 % point RH. Figure 9 shows the distribution of relative humidity in class width of 1 % point RH. The very high values are rare and barely to see, but exist.

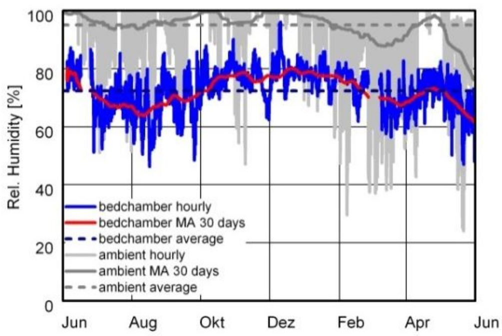

Figure 8 Relative humidity of bedchamber with monthly moving average, from 06/2009 until 06/2010 and ambient climate in background.

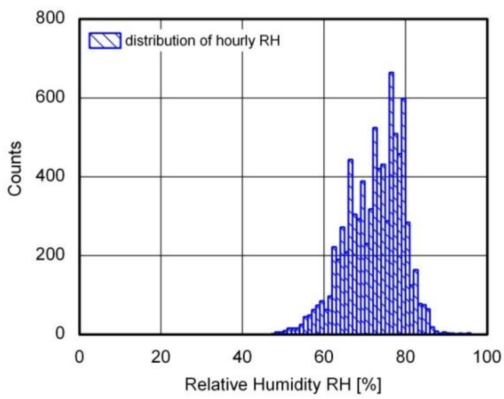

Figure 9 Distribution of RH in bedchamber with class width of 1 % RH, from 06/2009 until 06/2010

Daily fluctuation

The daily fluctuation is a common figure to evaluate the climate in a room. This information can be compared to figures given by means of preventive conservation. Holmberg [1] gives a limit of 15 % RH points for a daily acceptable range in unheated buildings. Burmester [2] gives for a museum climate 5 % RH points as acceptable limit. Due to ASHRAE [3] museum climate with a limit of daily fluctuations of 5% RH points is considered as a Class A museum. These are some examples for ongoing international discussions. Here it stands for some figures to get an idea of the climate situation in the bedchamber of Linderhof palace. In Figure 10 the daily fluctuations are shown with a daily maximum (blue line) and minimum (light blue line) value based on 5 minute measured data. The difference of daily maximum and minimum gives us the maximum daily fluctuation, depicted as dark blue graph. Some boarder lines indicate the bad climate situation with many fluctuations over 15 % RH points up to 25 % RH points.

A constant climate or RH level is not given in Linderhof palace. The RH follows an annual cycle as shown. In Figure 11 further examples for recommended room climates or possibilities for evaluation are given. The fluctuations of relative humidity are centred on the monthly moving average according to the "acclimatisation concept" of Bratasz [4]. A boarder line of ± 10 % RH points gives the limit of a museums climate of Class B according to ASHRAE [3].

4.2. Temperature

The graph of the air temperature in the bedchamber is shown in the Figure 12. The maximum of the hourly data is 24.8 °C and minimum - 1.4 °C. There seems to be some measurement fault at 0 °C. Comparing these values to additional measurements in adjacent rooms shows that lower temperatures could be possible in this period. The room temperature follows strongly the seasonal cycle of the ambient climate. The daily up and down is damped compared to ambient temperature. Average temperature of this year period is 11.67 °C.

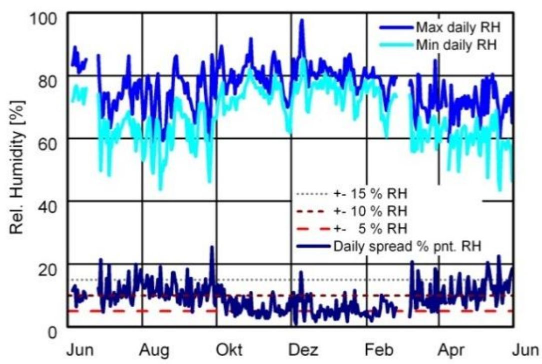

Figure 10 The blue line shows the daily maximum measured value, the light blue line the daily minimum measured value. The dark blue line shows the maximum daily difference (difference between blue und light blue lines) in RH from 06/2009 to 06/2010.

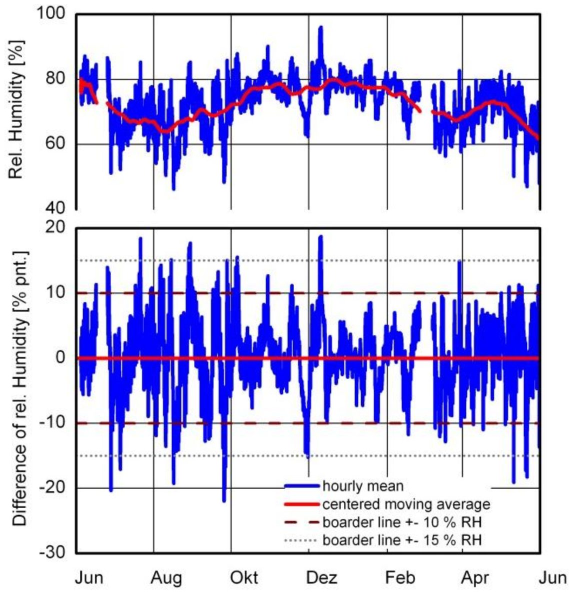

Figure 11 The upper graph shows with the blue line the measured room climate in RH of the bedchamber. The red line shows the monthly moving average. The graph below shows the fluctuation of relative humidity of the upper shown data centred on monthly moving average from 06/2009 to 06/2010.

In summer the maximum of monthly moving average is at 22.3 °C and the minimum in winter at 0.4 °C.

Calculating the difference of mean ambient and bedchamber temperature gives an offset of plus 6.2 Kelvin for the bedchamber. In summer the offset is a little bit higher at 7.2 K, in winter slightly lower at 6.0 K.

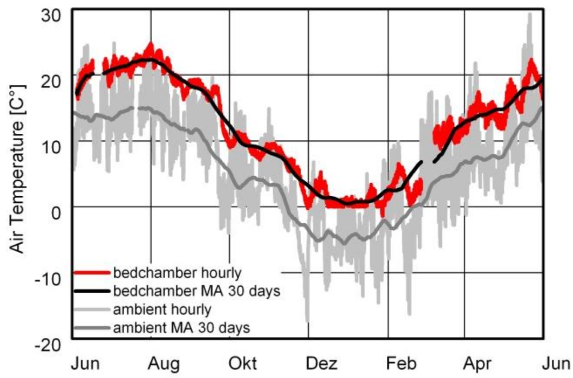

Figure 12 The red graph shows the air temperature with hourly data of the bedchamber, the black line is the monthly moving average. The grey lines show the data of the ambient climate analogue. Time from 06/2009 until 06/2010.

4.3. Absolute Humidity

Figure 13 shows the absolute humidity in the bedchamber in context to the ambient climate. Without water vapour sources and adequate airing the water content inside should be the same as outside. Visitors are the only known source of water vapour. This indicates the influence of the visitors to the room climate. A distribution of the visitors is given in Figure 15. Examining the water content of the calculated hourly data gives an average value of 8.12 g/m³. The maximum is given in summer with 17.27 g/m³ and a minimum with 2.98 g/m³. The monthly moving average (MA) gives the maximum of 13.49 g/m³ and the minimum of 3.92 g/m³. Calculating the difference between bedchamber and ambient water content gives inside a plus of 0.87 g/m³. In detail we can calculate a plus of water content in the bedchamber compared to ambient climate in summer (max) with 0.98 g/m³and in winter (min) with 0.79 g/m³.

Sultriness

Warm and humid air is referred to as uncomfortable climate conditions to humans and is called sultriness. There are some different definitions when sultriness starts. Scharlau [7] refers sultriness to the curve of Lancester-Castens, starting at a water vapour pressure of 1878 Pascal. A newer definition gives Steadman [5] with beginning of sultriness at 1600 Pa. Fiedler [6] combines Temperature with Humidity for his definition. For further considerations the definition of Steadman is used. A water vapour pressure of 1600 Pa corresponds to 12.07 g absolute water content per m³ air. Figure 14 depicts the three definitions of sultriness in context of hourly data of relative humidity and temperature in a scatter plot. Conducting the data gives in total 1295 hours of sultry conditions in this period of one year. During opening hours there are 630 hours with uncomfortable conditions of sultriness. In total there are 80 days with hours of sultry conditions. Figure 15 shows these days with the ratio of sultry hours to opening hours.

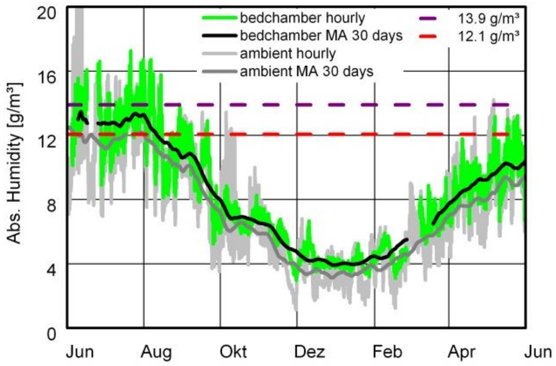

Figure 13 The green line shows the absolute humidity with hourly data of the bedchamber, the black line is the monthly moving average. The grey lines show the data of the ambient climate analogue. Time from 06/2009 until 06/2010.

5. BUILDING SIMULATION OF KING´S BEDCHAMBER

Conducting a building simulation is complex and time-consuming. For correct calculation all necessary boarder conditions have to be examined and determined thoroughly. The following chapter gives a short insight in first calculation results of dependencies of visitor influence, outer climate, and air change rate. The whole building model with boarder conditions will be highlighted in a further paper.

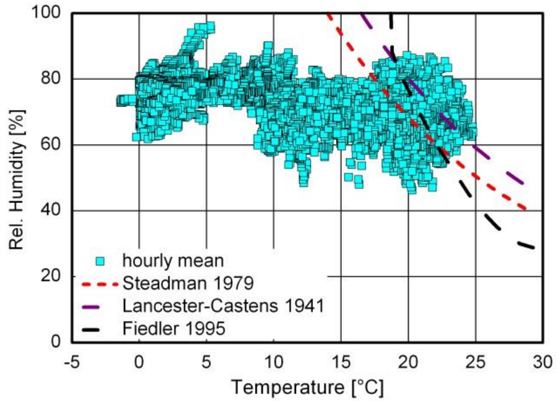

Figure 14 Scatterplot of the measured data of the bedchamber. Temperature and relative humidity of the hourly data is shown in this plot as a squared box. The measured data is related to the border lines of sultriness due to absolute humidity and temperature. Time from 06/2009 until 06/2010.

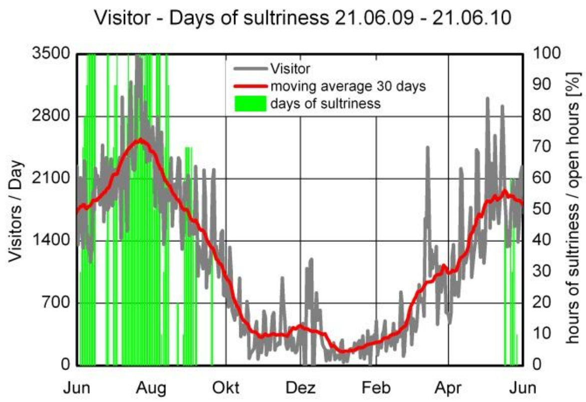

Figure 15 Days of sultriness in context of daily figures of visitors, from 06/2009 until 06/2010. Overall 80 days with definition of sultriness occur. The hours of sultriness are given in ratio to opening hours.

5.1. Simulation model

The building simulation model is based on the real building components partly introduced in this paper. Due to software limitations and to lower the work load some simplifications have been made in modelling the bedchamber. For example the round areas on ceiling and two room corners are implemented as areas without bending. Figure 16 shows the building model implanted in the software. For calculation purposes the single building components are allocated to single areas with same assembling respectively similar climate conditions.

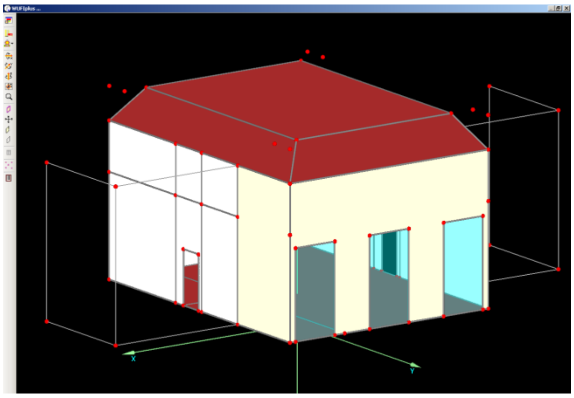

Figure 16 Building model of King´s bedchamber implemented in simulation software WUFI® Plus. The windows on north facade are imaged as light blue areas.

5.2. Simulation of visitors and air change rate

Investigations on the room climate in Castel Schönbrunn at Wien, conducted by KIPPES [8] shows that the air change rate has much more influence on room climate than the emissions of visitors. A new airing concept has been developed based on this thesis. The proposed measures contained a better sealing of the windows to reduce the influence of the outer climate.

As a first step a building simulation calculation was done with changed air tightness of the bedchamber in assumption of closed windows throughout the year. Due to this measure a maximum reduction of airing with outer climate should be reached. The air change rate was set to 0.13 h^{-1} in accordance to the lowest measured value of air change rate in winter time. The result of this simulation set up will be compared to the same simulation set up only distinguished between constant and as real assumed air change rate conditions.

The building simulation shows in Figure 17 the same relative humidity where the ACR are almost equal. During summer and autumn a rise of RH can be observed due to the reduce ACR.The absolute humidity also rises with the RH. Figure 18 shows the absolute water content. In this graph the boarder line for sultriness due to STEADMAN [5] is added. The already bad air conditions for the visitors are going worse. The hours and days of sultriness are doubling as figures in Table 1 show.

Also the concentration of carbon dioxide was measured and compared in building simulation. The results are depicted in Figure 19. The values of measured data and simulation data show a good accordance. The values of carbon dioxide are rising up to 4000 ppm in simulation results with reduced air change rate. The air quality is decreasing with rising carbon dioxide. Due to DIN EN 13799 [9] the air quality beyond the green line of 1400 ppm is bad.

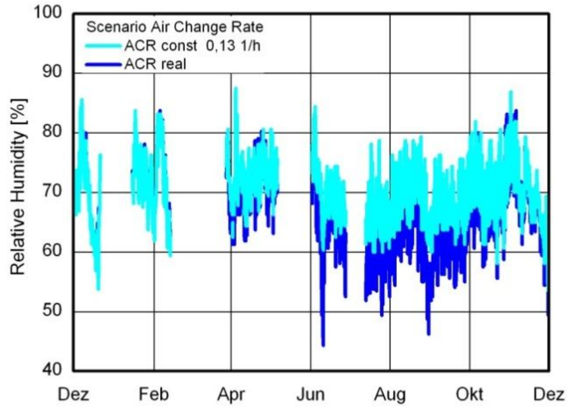

Figure 17 Relative humidity in room air of the bedchamber with results of building simulation under real conditions and scenario with constant air change. Time from 12/2009 to 12/2010. With the reduced ACR in summer and autumn the RH rises.

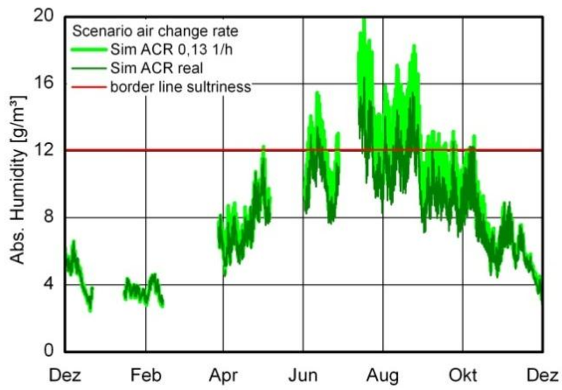

Figure 18 Absolute humidity of the bedchamber with results of building simulation under real conditions and scenario with constant air change. Time from 12/2009 to 12/2010. With the reduced ACR in summer and autumn the RH rises.

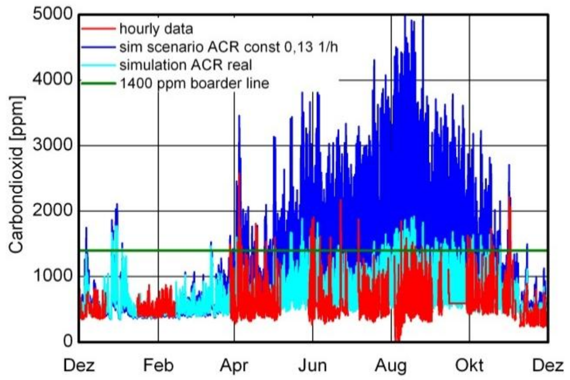

Figure 19 Carbon dioxide in room air of bedchamber, with results of building simulation under real conditions and scenario with constant air change rate compared to measured data. Time from 12/2009 to 12/2010.

Table 1 Days of sultriness as results of building simulation with real conditions compared to a reduced air change rate for the period from 12/2009 to 12/2010.

	Simulation real ACR	Sim ACR constant	Change [%]
Hours total	**782**	**1511**	**193**
Hours during opening	**372**	**790**	**212**
Days with sultriness	**55**	**108**	**196**

6. SUMMERY AND OUTLOOK

Knowledge about the building history and construction details is vital for understanding a building and its own special climate. In case of Linderhof palace the thorough construction is partly responsible for the considerable offset of about 6 Kelvin of the room temperature without any heating, beside visitors and lightning. The fluctuations of relative humidity were shown and set in context to internationally discussed values.

Very important to tourism in comfort (sultriness) and to the castle in preservation is the much higher absolute water content compared to the ambient climate. A precisely measurement is necessary to get true information to distinguish the influence of visitors in an offset of water content of air.

The real measured room climate of the King's Bedroom is replicated by computing a building simulation based on the adjacent room climates. First results illustrate the interrelationship of visitors and air change rate compared with the measured data of the King´s bedchamber room.

In order to adjust the simulation model to the real room climate further investigations are necessary. In order to proof the input parameters and adjust the model to the measured data of the room climate, sensitivity analysis will be made and their conformity will be compared with the real data. Further investigations on room climate and possible airing methods are necessary to improve the momentarily situation. With this generated building simulation model it will be possible to investigate different airing methods and their regulation and automatic control.

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