Building simulation modelling of the historic building Linderhof Palace taking account visitors

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Abstract

This paper is part of a research project for preventive conservation of cultural heritage of Fraunhofer Institute for Building Physics IBP at Holzkirchen called “Climate Stability of Historic Buildings”. Within this project the behaviour of the room climate in Linderhof Palace of the Bavarian King Ludwig II is investigated. The room climate plays a decisive role for the durable preservation of art. The real measured room climate is replicated by a building simulation model based on the adjacent room climates. The results are compared with the measured data of the considered room. In order to adjust the simulation model to the real room climate further investigations had to be made on building materials and construction details. By using a passive tracer gas method the air change rates of specific rooms were measured. Also a new model is developed and described to correctly simulate the influences of the visitors in Linderhof Palace. In order to proof the input parameters and to calibrate the model with the measured room climate sensitivity analyses were made and simulated data were compared with real data. Additionally the simulation is tested on a modified climate analysis which is typically used for preventive conservation. A scenario to the controversial discussed visitor´s influence is simulated regarding to proof the influence of visitors to the room climate and also to verify the simulation.

With this paper it is accomplished to grasp the complex boundary conditions and successfully apply them in a building simulation model of the Kings bedroom. The results of the computation fit well to the compared measured data.

1 Introduction

In the years 2008 to 2011 the behaviour of the room climate in Linderhof Palace 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 a building simulation was made with a special 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 the room climate of this unheated historic building, with a special focus on the room climate of the King’s bedroom. The translation of the building construction and adjacent room climate as boundary conditions to the simulation model are shown in detail. The room climate 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.

Up to 3000 and more visitors are coming to Linderhof Palace (Figure 1) per day in summertime. A special view will be given on the influence of the visitors to the room climate condition. Also the air change rate plays a major role. 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 few of the palace. The middle building section of the the right picture shows the three big windows of the bedchamber . (Source: Bayerische Schlösserverwaltung 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 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 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 opened to the public. Since this time the palace has been stayed unheated. In Figure 2 the different building phases are coloured and illustrated. The interior of the upper floor, where the show rooms are, is richly furnished. Figure 3 shows views of the king´s bedchamber. Almost every piece of the interior is a work of art.

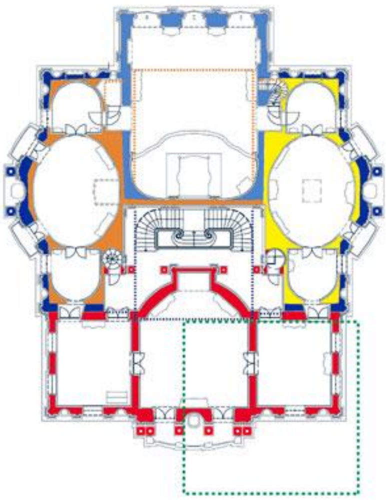

Figure 2: Upper floor of Linderhof palace with six building phases. The King´s bedchamber is the biggest room (light blue on top) and was accomplished only in the last building phase after the death of King Ludwig II in 1886. (Source: BSV).

Figure 3: 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 middle picture shows the north wall with the three big windows without curtains. The right picture shows the right window and wall corner seen in the middle picture with closed inner shutter and curtain. (BSV).

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 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 4. This component is also shown in Figure 8 with assembly within the building simulation software WUFI® plus.

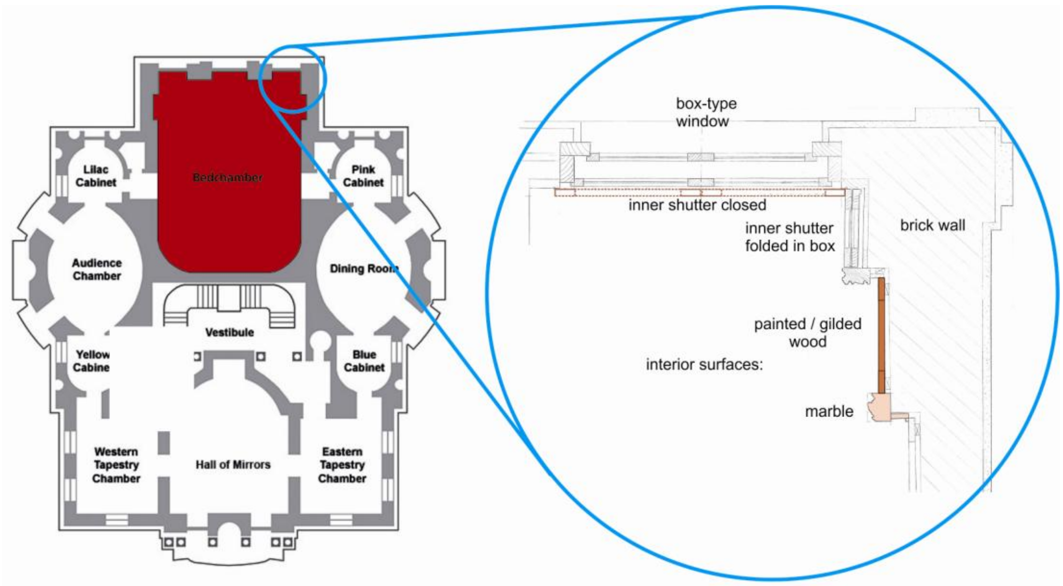

Figure 4: Detail of wall construction with interior surface consisting mainly of framed gilded or painted wood. The opened inner shutter is hidden in a lateral box.

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 were explanations are given through the tour guides. The tour route follows in the upper floor in clockwise direction, see green arrows in Figure 5. 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.

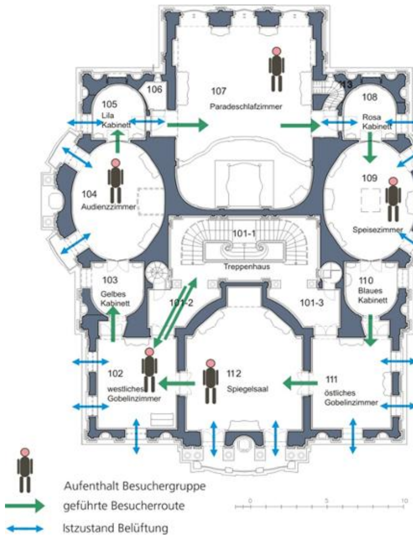

Figure 5: Upper floor with visitor´s route clockwise through the show rooms (green arrows). The blue arrows show the windows used by tour guides for airing. The windows in the bedchamber are never opened for airing. (BSV).

3 Measured climates

First measurements have started in February 2008. Here, the one year period from 1^{st} Dec 2009 to 1^{st} Dec 2010 is introduced. 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.

Relative Humidity of ambient climate 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 (Figure 9)

Temperature of ambient climate 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 2011) 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 simulation. 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. Figure 6 shows a cross-section of the bedchamber across the alleyway where the guided tours go through. The cross-section shows beside the construction the related indoor climates of two adjacent rooms in the same floor, void rooms above these rooms with wall areas to the bedchamber, all rooms underneath and the indoor climate of the attic.

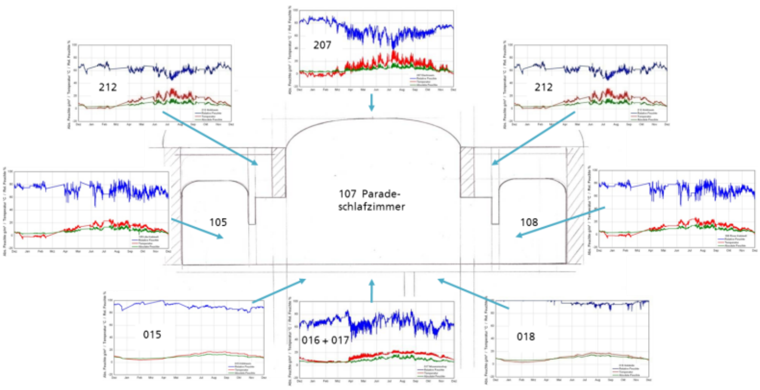

Figure 6: Sketch of upper floor with climates of adjacent rooms and ambient climate. The climate data are shown for the simulation year from 12 / 2009 to12 /2010.

4 Building simulation model

Congruent areas and volume

The calculation software WUFI® plus is based on the coupling of several one-dimensional calculations of the building components and their respective areas (Holm et. al. 2003, Künzel et. al. 2006). Inhomogeneous wall components and thermal bridges are not calculated within this software. There is principally a problem in assigning the actual measured dimensions to the simulation model, therefore simplifications have to be made. The construction areas and different component thicknesses from e.g. walls, ceilings and floors have to be considered and properly assigned to the model. For a congruent transformation of the real areas and volume to the simplified simulation model it was necessary to record the dimensions as accurately as possible. The exact determination of radiuses of curvature and arches was not possible due to the complex geometry and limited accessibility. The actual radiuses of walls and ceilings were approximated or estimated with circular and elliptical radiuses. To represent the real surfaces and cubature of the bedchamber the single (length) dimensions have been fitted to obtain an area and volume congruent model. The arches in the corners of the walls have been assumed in the model as a corner and the ceiling arches were simplified to 45 ° inclined surface. A comparison of the dimensions, areas and cubing of the model and from measurement obtained results gives a good accordance with a deviation from only 0 % to 2 %.

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 7.

Figure 8 shows the computer model and the construction assembly in the north eastern corner of the bedroom (see also Figure 4). 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 door visible 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.

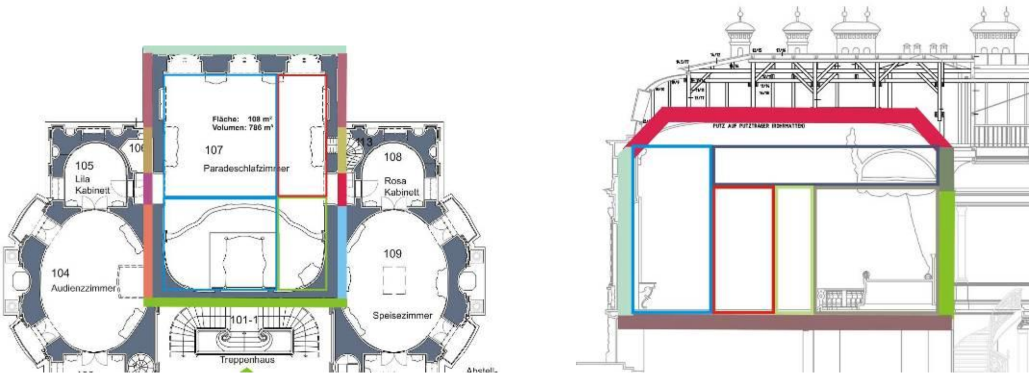

Figure 7: Upper floor plan with a sketch of the simplified room model of the King's Bedchamber with different wall partitions and their referred climate. The rectangle areas show rooms below in the ground floor with their arrangement in the building simulation. The right picture shows the model in cross-section lengthwise with referred building assembly and adjacent climate zones. (BSV)

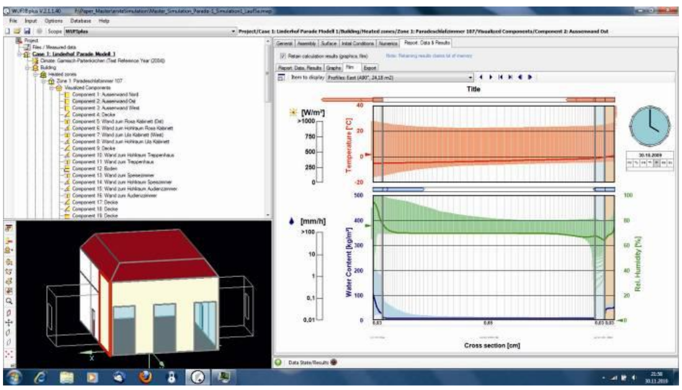

Figure 8: Screenshot of WUFI® plus simulation model of the King´s Bedchamber. A calculation run is shown of the building component "outer wall" as depicted in figure 4.

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, the green layer shows the band of relative humidity and the blue shows the water content.

Building components and material data

An example for a building component within the software is shown in Figure 8. For the simulation besides geometry data the material properties of each component are necessary. For hygrothermal calculations compared to pure thermal simulations additional material characteristics are necessary like porosity, moisture depending diffusion coefficient, capillary transport coefficient and moisture storage function. These data were retrieved from WUFI® plus database. There also exists an open accessible database, called MASEA® were common building materials are retrievable (www.irb.fraunhofer.de/denkmalpflege/angebote_partner/masea). The material properties of about 130 year old construction materials and building art works are not known and have to be assessed. Some hygrothermal characteristics from King Ludwig II times have been measured on reconstructed and real historic materials by (Wehle 2010). The characteristic data of three materials were taken from this work: gilded wood, painted wood and brocade silk.

5 Building simulation

Furnishing and fixtures

Also major furnishing and fixtures are included. In the bedroom are ovens, portals, balustrades, mirrors, furniture, cloth and a chandelier consisting mainly of materials like marble, brick, wood, glass, metal, porcelain and silk. These materials were assessed and roughly calculated as an additional thermal mass in the bedchamber of about 10.000 kg.

Fenestration and inner shutter

The U-value of the boxed windows is calculated according to DIN EN 10077-1. The window area for one window is 6.57 m² with an area share of window frames of 59 %. With a single glass on both frames and panels in the lower frame areas a U-value of 1.85 [W/m²K] was calculated. To each window a special inner shutter is arranged, see Figure 3. Every day the shutters are closed by the guides. The U-value therefore changes from day to night. A calculation of the inner shutter was conducted on the basis of DIN EN 1077-1. The U-value gets down to 1.32 [W/m²K] with closed shutter. Testing the influence of the U-value of the windows with a switching profile, gave almost no influence for U-values lower than 2 [W/m²K].

Results of first simulation

The following first simulation was fed with the additional annual mean values for boundary conditions and input data, shown in Table 1. For the inner sources average data based on typical values of vapor, heat and carbon dioxide production of humans are used. A more detailed discussion on air change rate inner sources is following later in this paper.

Table 1: Input data air change rate and inner sources of first simulation

First simulation	Annual mean values
Air change rate per hour (ACH)	**0.2 [1/h]**
Visitor vapor production	**3.4 [kg/d]**
Visitor heat production	**9.8 [kW/d]**
Visitor CO_2 production	**3.5 [kg/d]**

The results of the first simulation compared to the measured data of the bedchamber are shown in Figure 9. The red lines are the temperature curves of the simulation (SIM) as light red and measured values (MW) as a dark red line. A good accordance is given. More difficult to simulate and therefore with a special focus is the relative humidity. The dark blue line is the measured data (MW) and results of simulation (SIM). The simulation shows already a good accordance, but there are some certain deviations, too. Also the simulation result of absolute humidity is close to the calculated values of the measured data. The absolute humidity is calculated of relative humidity and temperature by empirical formulas.

In the hatched areas not all boundary conditions for simulation are fulfilled, i.e. data are missing of the measured adjacent climates. Therefore the hatched areas will be neglected in further interpretations.

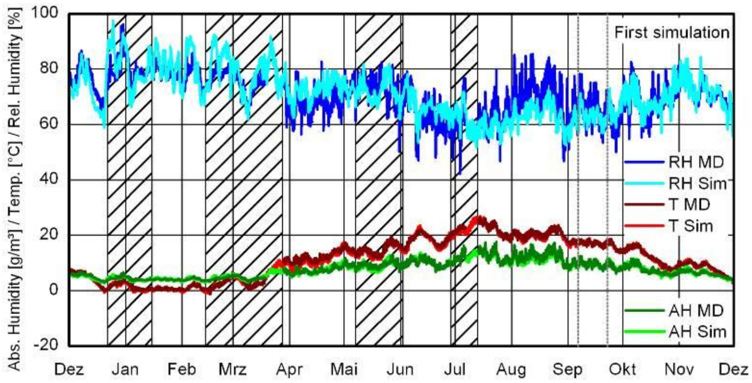

Figure 9: Results of first simulation compared to measured data of the room climate of the bedchamber. MD abbreviates measured data and Sim abbreviates results of simulation. The hatched areas will be neglected due to missing boundary conditions. Time period is one year from 12/2009 to 12/2010.

The graph in figure 10 compares simulation with measurement in regard to the 24 hour moving fluctuation range of relative humidity. Whereas in December the figures fit well, in February the fluctuation range of simulation is slightly higher. From April to end of October the fluctuations are far below and cannot give a correct image of reality. Only in November some accordance to measurement is observable. It is assumed that in periods of good accordance the actual boundary condition corresponds to the annual mean values at table 1. To get a better correspondence for the other periods, seasonal and hourly courses may be needed.

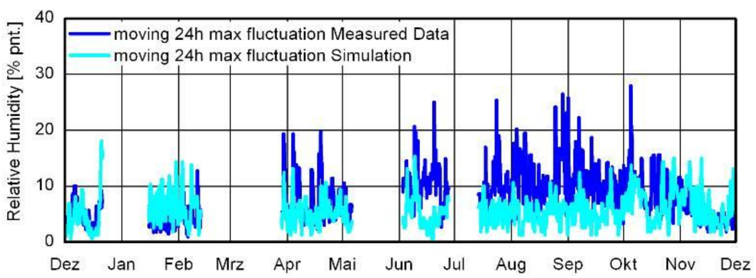

Figure 10: Comparing first simulation and measurement in maximum range of relative humidity in a moving 24 hour intervals for one year, only valid time periods.

Calibration, Validation and Variations of simulation

For testing and calibration of the simulation model respectively its parameters the input data are varied. The effects on the results are discussed with a special focus on relative humidity.

In table 2 the conducted simulations are listed. The colored marked lines indicate the discussed variations in this paper.

Table 2: Overview of different conducted simulations with variation of parameters. Variations marked in blue are discussed in detail. The sd-values corresponds reciprocally to perm values.

Simulation	profile ACH	profile inner source	profile interzone air exchange	material / s_d-value
First Simulation	constant	constant	-	default
Version 1	seasonal	seasonal	-	default
Version 2	seasonal	hourly	-	default
Version 3	hourly	seasonal	-	default
Version 4	hourly	hourly	-	default
Version 5	hourly	hourly	seasonal	default
Version 6	hourly	hourly	hourly	default
Version 7	hourly	hourly	seasonal	max buffering
Version 8	hourly	hourly	seasonal	min buffering
best fit	hourly	hourly	seasonal	best fit

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.

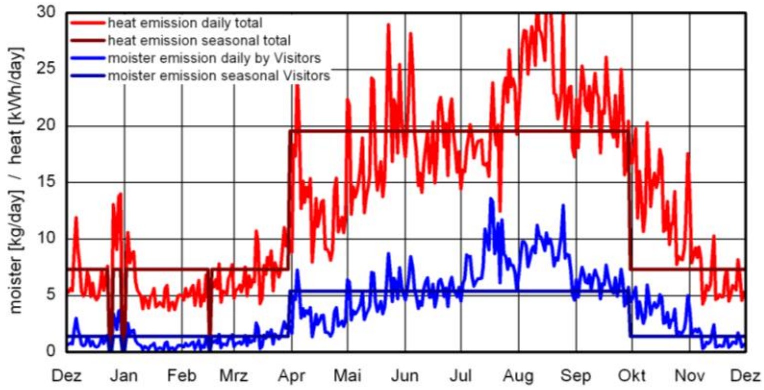

Figure 11: Detailed hourly profiles of equivalent staying visitors for heat and vapor emission in the bedchamber. Additionally the seasonal average profiles are shown.

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 11 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.

Ventilation profile with hourly data

The idea for an hourly ventilation profile derives from watching the ventilation behavior at the palace. A strong temperature and visitor depending ventilation behavior was observed. In summertime with many visitors and hot days almost every window is open, except for the windows in the bedchamber. In wintertime with only a few visitors and cold temperatures the windows are almost closed all day. Also a distinct day and night rhythm was observed due to mostly open windows during day and closed windows with closed shutter at night. Therefore detailed measurements on air change rate with passive tracergas method were performed (Kilian et.al, 2011). The hourly ventilation profile is calibrated on the measured air exchange rates and interpolated between these two fix points with a factor of the room temperature (Bichlmair 2011). Based on the winter measurement a constant air change rate is assumed throughout the year for infiltration leakage and as a general average profile for simulation scenario. Table 3 shows the mean values of air change rates for the building simulation. Figure 12 shows the different used ventilation profiles.

Table 3: Mean values of air change rates ACH for the building simulation.

Air change rate per hour ACH	Day (summer) [1/h]	Night (summer) [1/h]	Summer [1/h]	Winter [1/h]
Simulation	**0.469**	**0.101**	**0.261**	**0.126**

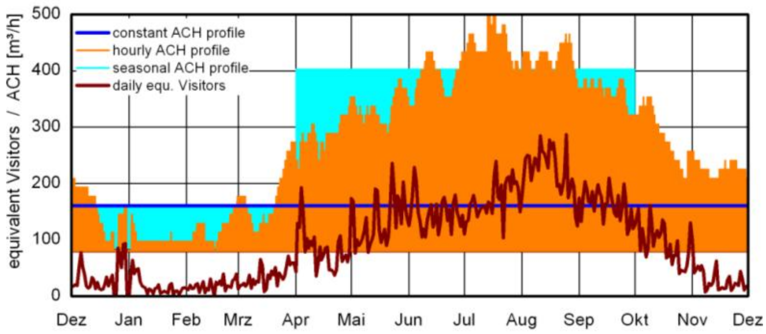

Figure 12: Temperature and visitor depending ventilation profile with hourly data (orange line), seasonal and constant profiles for the period from 12 / 2009 to 12 / 2010. Additionally the equivalent Visitor profile is shown (brown line).

Interzone air exchange

The doors between the bedchamber and the adjacent rooms are always open. Therefore interzone air exchange is possible. An estimation based on the measured air change rates supposes an interzone air exchange rate of 1.5 [1/h] for summer measurement and 0.9 [1/h] for winter measurement to the volume of the bedchamber. With additional airflow measurements this figures were confirmed. However, these figures give only a rough estimation for some single measurements.

The interzone air exchange is composed of an air flow from outside due to ventilation and an additional air flow conditioned to the climate of an adjacent room. In version 5 and 6 of the simulation (see Table 2) two different profiles (seasonal and hourly) were tested, whereas for an hourly profile no improvement could be observed. A considerable improvement was made in accordance of relative humidity with version 5 (seasonal profile) especially for the summer period from July to September. Only a slight improvement was observable for relative humidity fluctuations.

Moisture buffering of interior

The above mentioned furniture and fixtures and also the inner layer of all components are essential for the hygrothermal behavior of a room. Within the project "Climate Stability of Historic Buildings" the moisture buffering characteristic of indoor surfaces and their effects on indoor environment was of special interest. The surface of the pompous historic interior consists of decorations with cloth, paintings and carved gildings (for an image see figure 3). All of this lavish artwork, decors and ornaments have a much bigger surface compared to a simplified component assembly. As a result an additional surface area of about 534 m^2 was added in the model. With this the simulation got more realistic.

Also unknown are the real transient conditions of the surfaces and the real material characteristics of the different material layers near to the surface. A special feature of the software is a hypothetical vapor retarder layer on the surface which can be implemented. With this tool it is possible to regulate the moisture buffering performance of the components. An additional s_d-value of 0.328 [m] (equals to 10 perm [ng/(Pa*s*m²)] SI) was chosen on all surfaces, for the first simulation. This seemed to be necessary for the ceiling with painted gypsum plaster, painted wood and gilded wood to simulate these very first layers. Only the brocade silk kept its experimental measured value. A detailed description of the moisture buffering effect on hygrothermal simulation of a historic building and newly measured hygrothermal characteristics of historic materials is given in (Wehle 2010).

With version 7 and 8 of the simulation (see Table 2) the effects of moisture buffering are tested. In version 7 the additional surface s_d-value is set to 0.5 [m]. The expected effect of lower moisture buffering is observable. In consequence the fluctuations of relative humidity increase. No further increase of fluctuations can be observed with a much higher s_d-value of 1.0 [m]. In version 8 no additional surface s_d-value was set. The effect shows in much lower fluctuation ranges of RH compared to measurements. For the best fit simulation the s_d-value was set to an average of 0.328 [m] for every material.

Best fit simulation

Compared to the first simulation following improvements were done: hourly profiles for visitors (heat, moisture, carbon dioxide), hourly profiles for ventilation, interzone airflow, optimized moister buffering. The best fit simulation shows a good accordance in RH to measurements, see Figure 13. In February the RH level is a little lower and in June the RH level is slightly higher compared to measurement. Overall the RH is in average slightly lower compared to measured data. Looking to a statistical evaluation with box plots the differences can be evaluated for the six valid partitions (TB 1 to TB 6) of the simulation year. The box and whisker plots show the overall range, average value and median. The box shows the 20^{th} and 80^{th} percentile, and the cross marks the 1^{st} and 99^{th} percentile. Partition TB 1 and TB 2 (December to February) show a lower level of RH as was seen in figure 13. In partition TB 5 and TB 6 (July to November) we can discover a slightly lower average value compared to measurements, the range of RH fits quite well. The last boxplot gives an overall view to simulation and measurement with an average von 67.7 % RH compared to 69.5 % RH of measurement. This difference lies within the measurement uncertainty of the sensor equipment used for measurements (± 0.5 K, ± 3 % RH).

Fluctuation range of relative humidity

Figure 15 shows the derived 24 hour moving fluctuation range in RH of best fit simulation compared to measurement. There is a good accordance even the highest fluctuation ranges are almost reached.

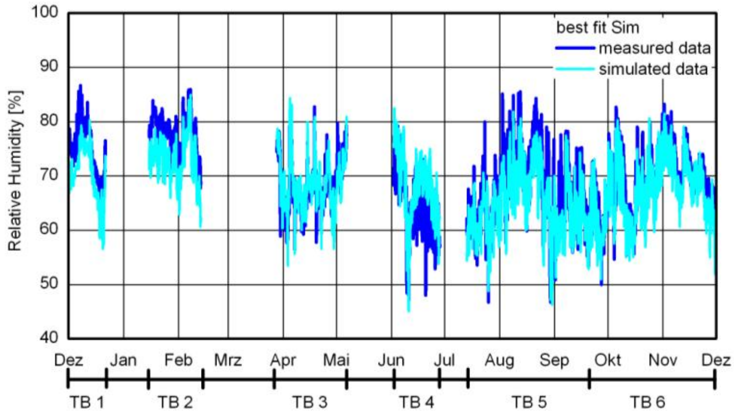

Figure 13: Comparison of best fit simulation and measured data in relative humidity (RH) for one year from 12 / 2009 to 12 / 2010.

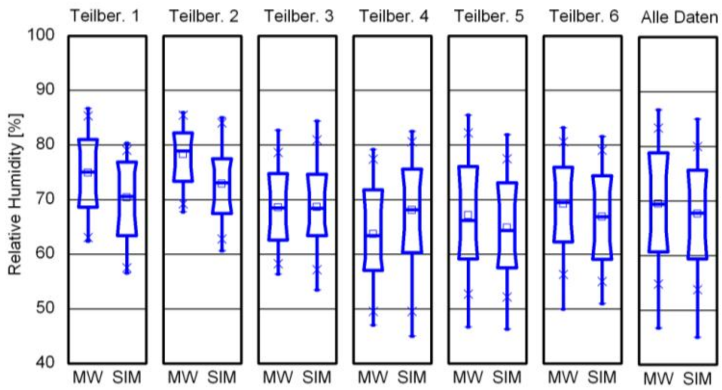

Figure 14: Comparison of best fit simulation (SIM) and measured data (MW) of relative humidity (RH) with box plots, divided into six periods (TB 1 to TB 6) analogous to Figure 13 and whole data for one year from 12 / 2009 to 12 / 2010.

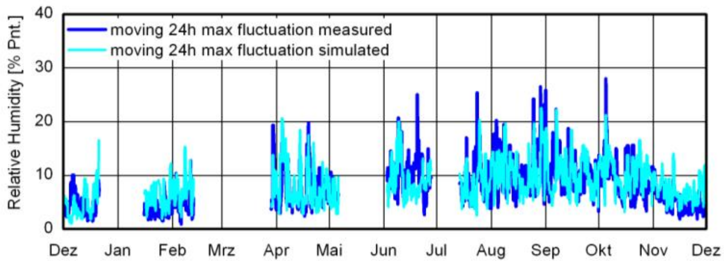

Figure 15: Comparing best fit simulation and measurement in maximum range of relative humidity in a moving 24 hour intervals for one year, only valid time periods.

Scenario of king´s bedchamber without visitors

This simulation was done on basis of best fit simulation but without interzone air exchange, without visitors and therefore with a constant air change rate ACH of 0.15 h^{-1} throughout the year. Figure 16 shows lines of monthly moving average (MA) of absolute humidity (AH) of the bedchamber (red line) based on hourly measured data. The light blue line is the MA of the realistic simulation (realistic emission profiles of visitors, realistic air change rate, no interzone air exchange). The absolute humidity of the simulation equals quite good to measured data. Only the summer period is something to dry, as discussed above.

The green line gives the absolute water content as MA of the ambient climate. The difference in AH between bedchamber and ambient climate derives from the emission of the visitors. If we take out the visitor emissions for the simulation the same absolute humidity is expected. The dark blue line shows the absolute humidity of the simulation and lies almost exactly on the green line. This scenario confirms the thesis of the influence of the visitors.

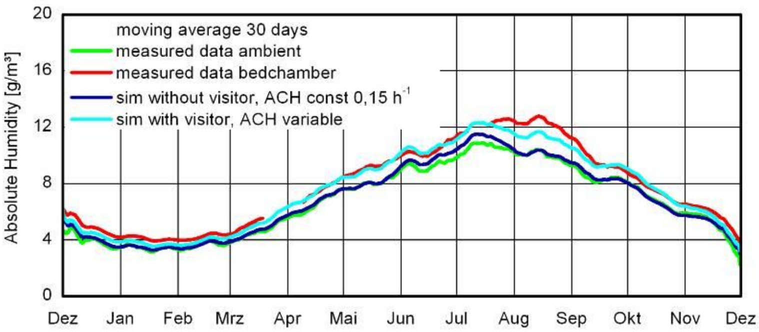

Figure 16: Absolute humidity (AH) of measured and simulated data of king´s bedchamber with scenario without visitors and ambient climate. The influence of visitors is clearly recognizable.

6 Conclusions and Outlook

With a rough implementation of the building and the boundary conditions a fairly good correspondence to measured data may be reached. However, a closer look to the simulated data reveals some weaknesses and a discrepancy especially in relative humidity fluctuations. In further simulations influences of different input data were investigated. With more detailed data an essential improvement in accordance of relative humidity and 24 hour fluctuation of relative humidity was achieved. Additional investigations were done with varying moisture buffering and interzone air exchange. This procedural method is more than a calibration on measured data. This new approach is a helpful possibility for validation concerning the special purposes of preventive conservation. This is important for statements in sense of preventive conservation for possible damages to materials of vulnerable artworks. Further investigations are in preparation to improve the simulation on multizonal airflow and climate behavior with scenarios to visitors and new airing concepts.

7 Acknowledgements

These examinations are part of the national project “Climate Stability of Historic Buildings” and of the European large scale integrating project “Climate for Culture – Damage risk assessment, economic impact and mitigation strategies for sustainable preservation of cultural heritage in the times of climate change”, supported by the European Commission under the

Grant agreement no.: 226973. FP7-ENV-2008-1 Theme 6 Environment (including climate change). The authors like to express their sincere thanks to the Bayerische Schlösserverwaltung for supporting the project.

8 References

ASHRAE Handbook HVAC Applications, 2011. Chapter 23: Museums, Galleries, Archives and Libraries.

Bichlmair, S. 2011. Simulation und Analyse des Raumklimas in ausgewählten Räumen im Schloss Linderhof, Master Thesis, Rosenheim, 2011.

Bichlmair, S. & Kilian, R., 2011. 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. In Developments in climate control of historic buildings. Fraunhofer IRB Verlag, Stuttgart.

DIN EN 10077-1. Thermal performance of windows, doors and shutters - Calculation of thermal transmittance. German Version EN ISO 10077-1:2006 + AC:2009

Holm, A., Künzel, H.M., Sedlbauer, K., 2003. The hygrothermal behavior of rooms: Combining building simulation and hygrothermal envelope calculation. 8th IBPSA Conference, p. 499-506, Eindhoven, Netherlands 2003.

Kilian, R., Bichlmair , S., Wehle, B.& Holm, A., 2011. Passive sampling as a method for air exchange measurements for whole building simulation of historic buildings. 9th Nordic Symposium on Building Physics, NSB 2011, Proceedings V3, p. 1135- 1142, Tampere University of Technology, Tampere, Finland.

Künzel, H.M., Sedlbauer, K., Holm, A. & Krus, M. 2006. Entwicklung der hygrothermischen Simulation im Bauwesen am Beispiel der Softwarefamilie WUFI®. In: wksb, V. 55, p. 7-14, Ludwigshafen 2006

Wehle, B.2010. Simulation des Raumklimas unter Berücksichtigung der Feuchtepufferungseigenschaften des Türkischen Saales im Königshaus am Schachen, Diploma Thesis, Rosenheim 2010.