VALIDATION OF A LOW-ENERGY WHOLE BUILDING SIMULATION MODEL

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ABSTRACT

A methodology for validating low-energy whole building simulations is expounded in this paper. The capability of the integrated building-plant system, modeled by means of equation-based environment (IDA ICE), is evaluated to quantify model mismatch. A unique “energy concept” building is considered, and consists of various low-exergy technologies: suspended ceiling panels with phase change material (PCM), radiant cooling by plastered capillary tubes, borehole heat exchanger, and free night ventilation. Monitoring data is used to validate the model over the cooling season, and results showed accurate prediction by both the building and plant models (Pfafferott 2003). The primary outcome of this research is the complete, integrated realization of a low-energy whole building simulation with validation results, whereas comparable “energy concept” validation studies are scarce. Furthermore, the high accuracy of the approach lends itself to optimization of low-energy buildings, the investigation and demonstration of alternative cooling strategies, and in support of the construction of such buildings.

INTRODUCTION

In whole building simulation studies many parameters must be considered, especially when new, advanced building energy technologies are used simultaneously. In general, the interaction between climate, occupants, and HVAC in modern buildings is sufficiently complex that building energy behaviour can be comprehended only by resorting to simulation. For these concerns IDA Indoor Climate and Energy (Björsell et. al. 1999; Achermann, M. 2000), a dynamic multi-zone application for accurate study on thermal comfort and energy consumption, is used in this study. The objective being to validate the building model using a detailed monitoring data.

BUILDING DESCRIPTION

General information

The Engelhardt and Bauer (E&B) GmbH printer office building, located in Karlsruhe and constructed in 2006, is the subject of this study (Pfafferott et al. 2006). The building was renovated according to the EnOB program: research in energy-optimized construction founded by the German Ministry of Economics and Labour BMWA. The concept was to build an efficient office building with low-energy consumption and high workplace environmental quality. The internal space is distributed on two floors with the direction North-West as main orientation. The ground floor is characterized by the workspace, service area, and atrium. The first floor has open workspace and some private offices. The main characteristics of the building are reported in the Table 1.

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<tr>
<td>1160</td>
<td>3900</td>
<td>2</td>
<td>258/237</td>
<td>7-18</td>
<td>0.30</td>
<td>1.4</td>
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From a technological viewpoint, the building shell is designed to thoroughly restrain energy flux from the external environment: the walls and the roof are characterized by a large insulation (12 cm of mineral wool). At the same time, a large fenestration area is used to increase natural lighting levels, while still being characterized by high thermal insulation level. Hence, the local discomfort caused by warm/cold surfaces is drastically reduced. The roof is a lightweight technology characterized by steel structure, whereas the walls consist of concrete brick. The U-values of the external components are [W/m²K] as a
following reported: walls 0.3, base plate 0.27, roof 0.2 and windows (glass plus frame) 1.4 with the g-value equal to 0.6. Considering the thermal bridge effect, the overall U-value of the building is 0.54 W/m²K. Thermo Active Building Systems (TABS) (Koschenz et. al. 2000; Meierhans 1996) are used as efficient cooling devices allowing the use of high temperature level and low energy demand (Kalz 2009). In order to facilitate passive cooling in spite of high solar and internal heat gains, the intermediate concrete ceiling is exposed and the capillary tubes are used to activate the thermal mass. The ceiling panels on the first floor contain the phase change materials (PCM) that enforce the thermal storage effect.

**Shading devices**

The large glass façade opens the building to the West and provides a good view for all employees working in the office. The West façade and the other windows are protected with automatic external solar shading systems that are controlled, with an on-off algorithm, according to the direct solar radiation (i.e. when the radiation is higher than 200W/m², a sensor controls the moving of the shading devices).

**Mechanical and natural ventilation**

The mechanical ventilation ensures the minimum required ventilation flow (40-60 m³/h per person), with heat recovery systems in winter and during the summer when the ambient air temperature is high. Moreover, in the winter, due to the high heat-recovery efficiency of 80%, the ventilation system runs without supplemental heat. The basic mechanical ventilation can be enhanced by free ventilation since the occupants may individually open the windows. Free night ventilation is driven by the buoyancy effect and it utilized the cool night air for cooling the building structure. The night ventilation openings open automatically between 1 and 4 a.m. when necessary.

**Heating/cooling concept**

The entire building is heated exclusively by waste heat from the printing plant by employing low temperature radiators and radiant floor heating. The new cooling concept relies on the use of environmental energy, the good insulation of the envelope and the use of natural heat sinks (air and ground). The Figure 3 shows the cooling concept adopted.

In particular, the system is based on the following technologies:

- grid conditioning (capillary tubes) which is mounted in plaster on the massive intermediate ceiling;
- suspended radiant cooling panels with PCM;

**Internal gains**

The building is characterized by high internal gains mainly due to the high office equipment (printer, PC, light, plotter etc). A short monitoring campaign was carried out to evaluate the actual internal gains intensity due to equipment, occupancy, lighting, etc. The monitored output values were used to create a mean internal gains schedule for the simulation model. Based on the energy meter recordings, the internal gains during working days were determined to be nearly 250 Wh/m²d). It is assumed that, during the night, being the office empty, the heat load is approximately 10% of the maximum load.

**Figure 1 North-west façade of the building**

**Figure 2 Typical internal gains**

**Figure 3 Cooling strategies**
the use of the ground as a natural heat sink (the bore-hole heat exchangers are directly driven without a mechanical chiller);

- free night ventilation from automatically controlled openings.

In detail the first floor is cooled by means a radiant cooling with plastered capillary tubes on the massive intermediate ceiling. Further, novel radiant cooling panels with Micronal® PCM suspended from the ceiling provide to cool the floor (Figure 3). The application of 12 vertical bore-hole heat exchangers, with a depth of 44 m, allows the use of the ground as a heat sink and provide 40 W/m of cooling energy. The borehole heat exchangers are driven without a mechanical chiller. Furthermore, the bore-hole heat exchanger and the Thermo Active Building Systems (TABS) are not separated by a heat exchanger, and the volume flow is directly related to the cooling devices (no additional chiller is used), creating a streamlined system. In the Table 2 are summarized in the plant systems strategies.

Table 2 Plant systems strategies

<table>
<thead>
<tr>
<th>COOLING</th>
<th>HEATING</th>
<th>HEAT SOURCE</th>
<th>HEAT SINK</th>
<th>VENT.</th>
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<tr>
<td>Grid conditioning</td>
<td>Suspended ceiling panels</td>
<td>Radiator</td>
<td>Floor heating</td>
<td>Wasted heat</td>
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Weather data

Knowledge the real weather data is essential in the building model validation. Weather data from the Meteorological Institute of the University of Karlsruhe was adopted, even though the data was measured a few kilometers away it provides a good estimate. The monitoring data contains, however, only the global solar radiation. The IDA ICE requires the direct solar radiation to calculate solar loads across the windows. The TRNSYS simulation tool, through the use of the solar processor, is used in order to split the global radiation in diffuse and direct component knowing the relative humidity, the air temperature and the geographical position. Figure 4 shows the monitored ambient air temperature during July; the values are over 28°C only for few days. The night temperature level never exceeds 22°C so it is possible to take advance from the night ventilation strategy. The ground characteristics are evaluated by means of a thermal response test. In particular the undisturbed ground temperature is equal to 14.5°C.

Figure 4 Ambient temperature and direct solar radiation

METHODOLOGY OF VALIDATION

The validation is defined as the process of determining that the model on which the simulations is based is an acceptably accurate representation of reality.
Its demonstration is very complicated and time consuming operation and it is unfeasible without well known boundary conditions. The methodology adopted consists of three different steps as shown in Figure 5. The first step consists of collecting all the necessary input data and to build the simulation model (geometry and equipment). During the second and third step, the model is calibrated and the results validated by comparing monitored data, respectively. The validation analysis was performed with monitoring data collected in July 2008. The two different simulation steps have been defined considering the complexity of the validation/calibration procedure. In fact, when so many parameters influence each other, it is better to analyze the problem for degrees of complexity. According to the methodology, the second step considers different inputs (mass flow, temperature, time operation, etc.) separately with respect to the output (open loop plant systems). The third step analyzes the real operation of the building with a closed circuit between cooling devices and borehole heat exchangers. This procedure permitted to analyze the performances of both suspended ceiling panels of the first floor and capillary tube of the ground floor and, moreover, analyze the interaction between the building component and the surrounding (ground and ambient air).

**BUILDING MODEL**

The building model is determined according to the design documentation and the drawings available. Moreover, the precondition for a good model-based evaluation is create a close image of the building and its technical equipment. In any specific case, the modelling of the equipment and supply systems operation was considerably supported by the presence of detailed monitoring data. There are four building zones: Zone 1, not considered in this study (no monitoring data are collected); Zone 2, ground floor in which the grid conditioning are used to cool the air; Zone 3, that connects the Zone 2 with the Zone 4. The latter zone is called by suspended ceiling panels.

![Figure 7 Vertical section of the building model](image)

![Figure 8 3D view of the building model](image)

When the geometrical model is build the plant system components can be added or modified according to the real design. Particular attention was paid to the radiant cooling panels of the first floor. Since no standard components to simulate a PCM cooling ceilings panel are available in IDA-ICE, a combination of two separate models is used. In particular, the TABS model is coupled with the PCM model in order to describe the real heat transfer between the component and the air. The available PCM model is analyzed and modified in order to find a good approximation between simulation model and real case. A new equation to find the variable heat capacity is implemented in IDA-ICE environment using a NMF language by using differential-algebraic equations (Sahlin 1996). The new equation to model the PCM heat capacity and melting point is created fitting with a parametric equation the measured data (melting and solidification curve).
VALIDATION RESULTS
The complete building model is composed by different simulation components: building envelope, borehole heat exchanger, TABS, suspended ceiling panels with PCM, pumps etc. The boundary conditions, the climate data, the characteristics of the ground, the operation plant (mass flow, temperature inlet etc.) are known with certainty. The process of validation consists on the comparison between the simulation results and the monitoring data of the real building. The simulations are tested during July 2008 (in this month are collected the most complete monitoring data) and the following parameters are analyzed:

- Operative room temperature [°C],
- Supply and return water temperature in the ceiling panels and in the ground [°C],
- Heat flux from the cooling devices (suspended ceiling panels and capillary tubes) [kW]

Operative room temperature
The operative room temperature (°C) (ORT) is the first parameter analyzed. The hourly simulation results, reported in the Figure 9, match well with the monitored room temperature, only a few daily peaks differ slightly from each other; this is mainly due to an under/over estimation of the internal heat loads and of direct solar radiation. The relatively large fluctuations of the measured temperature levels in the night and morning hours are interesting. This effect is due to the night ventilation, or to the manual morning free ventilation. The monitoring data shows that, during the morning hours, there is a fast ambient temperature fluctuation. This is caused by night ventilation or manual ventilation, where the globe thermometer seems particularly sensitive to the cool air.

Once the ventilation is completed the globe temperature immediately raises 2-3 K. The globe thermometer responds obviously quickly to the cool air movements. However, these values match well, with deviations below one Kelvin: the mean simulated temperature during the entire period differs by only about 1% of each other, Figure 10. Thus, both the gains and losses of the model seem to be very close with the real building operations. Moreover, in the next subchapter all the components are analyzed.

Heat fluxes
The correlation between monitoring and simulation results is evaluated considering the heat fluxes from both the cooling devices: suspended ceiling panels and grid conditioning. We expect that, the analysis conducted considering the models under comparable operating conditions, provides a close cooling performance. Boundary conditions are determined as the real operation by setting the inlet water temperature and volume flow. As reported in the Figure 12 and Figure 13, the results match well. This means that the heat transfer processes are well represented. In particular, the results reported in Figure 11 show that the PCM component (characterized by the moving heat capacity according to the ambient temperature) is an accurate description of the real operation both the phase change temperature (23 °C) and the heat capacity.
Moreover, a calibration of the heat transfer coefficient of the ceiling surface is necessary. The selectable parameter $h$ (W/m²K), represents the overall heat transfer coefficient (convection and radiation) from the cooling medium to the air and other component, is changed in order to find the best results. A small $h$ value corresponds to low ceiling power. Increasing from 10 to 15 W/m²K, the return temperatures are closer to the reference. Therefore, $h$ is set equal to 15 W/m²K, which achieved a good match in return temperatures. The Figure 14 shows the return water temperature from the cooling device. There is a good match with the measured values, the high water temperature level are due to a break in return temperatures caused by temporary standstill of the pump with resulting warming of the water stream of the pipes. So, finally the TABS and the ceiling panel model (even though very simple) well approximate the behavior of real operation.

**Supply water temperature**

The building model is coupled with a borehole field heat exchanger that supplies water directly to the cooling devices without further compressor cycle. In this work the IDA-ICE borehole model (Moosberger S. 2009) is coupled after some stand-alone validation test. It is a 3D model: cylindrical 2D fields are implemented around each borehole and 1D vertical field for the undisturbed ground temperature. The heat transfer in a BHEX involves a number of uncertain parameters, such as the ground thermal properties, the backfill thermal properties, the ground temperature or even the liquid inlet temperature. The Figure 15 shows that if the ground parameters are well known, the simulation results match well with the measurements. From the same graphics is shown that for very low mass flow values, the outlet water temperature became high. The mean difference between simulated and monitored values is equal to 0.2 K.
The comfort analysis

The comfort level is evaluated according with the adaptive comfort model, described by the European standard EN 15251:2007:2008. This model assesses the comfort level depending on the outside air temperature and assumes that the users can contrast the increasing temperatures changing the clothing level or through the windows opening. The operative room temperatures of the first level, calculated from the model, as well as the measured values are analyzed in the Figure 16. The comfort levels are very close. The monitored value shows lower ORT level due mainly to the sensitivity of the globe thermometer to the fresh morning air. Moreover, neither in the upper floor nor in the ground floor the comfort class C can be kept. In the upper floor an excess frequency of 6% is to be stated (is to be found out) in the model or 10% in the real building. In the ground floor it lies even with over 15%. Thus, in the building only about half of the present persons with the thermal comfort are satisfied.

Energy analysis

Considering the validated model, a study of energy flux helps to understand the building behavior and the cooling devices performances in order to define further optimization and provide guideline to reach at least the comfort Class B. The building energy balance is done in daily basis, as reported in Figure 17. However, with regard to the energy balance the calibrated IDA model gives a clear idea of the contribution of the different strategies.

For example, from the daily energy balance can be observed that the day ventilation is counted some days as losses and some days as heat gains, according to the ambient air temperature.

The Figure 18 shows the energy balance over the month of July. It is interesting to notice that the cooling is supplied in the same parts by free night ventilation and by cooling devices (21%). This fact does not correspond with the design phase, in which the night ventilation was designed to operate only in supporting to the mechanical cooling. Although, the cooling circle pump is in operation for about three quarters of the total time. This because of high supply water temperature from the borehole field that was about 20-21°C, too high, obviously, to lead away the high heat gains. Moreover, the hydraulic network was designed for a temperature difference of 6 K and not 2 K and hence, for a lower volume flow. On the other hand, the big influence of the night ventilation is due to the ambient air temperature difference that is often higher than 10 Kelvin. This big temperature difference depends on the fluctuations of the outside air temperature that during the night is always below 20°C.
The internal heat loads of about 250 Wh/m² and working day caused mainly by extensive computer equipment and lighting are a big part of the overall heat gains (21%). Moreover, the solar gains (28%) increase the overall gains, due to the large windows and its high g-value (0.6). The necessary mechanical day ventilation, considered over the simulation time contribute to increase the internal loads (2%).

CONCLUSION

This paper described the building model validation of the low-energy building located in Karlsruhe (Germany). Several simulation tools are available today on the market but not very often they are used for whole-building simulation analysis. This paper describes the methodology adopted and the results quality obtained in the real building analysis. The results showed, if the boundary conditions are well known, accurate prediction by both the building and plant models are possible. The primary benefit of the methodology is the complete integrated realization of a building simulation model. Furthermore, the high accuracy of the approach lends itself to allow optimization of the low-energy building, the investigation of alternative cooling strategies or in different climates. Moreover, the model can be used as support in designing similar constructions.

ACKNOWLEDGEMENTS

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REFERENCES


