DEVELOPMENT OF A CALIBRATION METHODOLOGY FOR THE ENERGY SIMULATION OF AN EXISTING BUILDING FROM 1969

Tobias Leibing\textsuperscript{1, 2}, Claudius Reiser\textsuperscript{1}, Oliver Baumann\textsuperscript{1}  
\textsuperscript{1}Ebert & Baumann Consulting Engineers Inc, Washington DC, USA  
\textsuperscript{2}Biberach University for Applied Sciences, Biberach, Germany

ABSTRACT

The increasing need for building renovation to meet new energy efficiency requirements is accompanied by a growing demand for whole building energy simulations. To have a simulation model that reflects the as-is conditions and is calibrated to measured energy consumption and performance is key to make a profound statement about the potentials of proposed energy conservation measures.

There are a lot of theoretical methodologies available for how to calibrate simulation models; however, they are often not suitable for a cost effective day-to-day practice.

The scope of the case study presented in this paper is to develop a methodology for building calibration based on an existing hotel building with the following major topics:

1) Description of a practical calibration methodology
2) Challenges and pitfalls of the calibration of an existing building
3) Identification of the minimum project information required
4) Definition of the quality grade of the final simulation model

As part of the Net-Zero Energy Commercial Building Initiative (CBI) of the U.S. Department of Energy an existing hotel building from 1969 was outfitted with extensive monitoring equipment in conjunction with the Pacific Northwest National Laboratory (PNNL). Thus, detailed insight in the building operation could be used to calibrate the HVAC (heating, ventilation, air conditioning) systems as well as the occupancy. Based on this information, the influence and sensitivity of single systems as well as the building in its entirety could be analyzed.

The intent of this paper is not to discuss actual energy saving measures.

INTRODUCTION

The project which formed the basis for this case study is a hotel building constructed in 1969. Located in the metropolitan area of Washington D.C., the climate can be described as mixed-humid (ASHRAE 90.1-2007, Appendix B).
Although refurbished partially over the course of time the age of the building is reflected in the overall condition of the HVAC systems.

The composition of the building follows a typical hotel layout, with a two-level podium accommodating the common areas and an 11 storey tower providing space for about 300 guestrooms. Main occupancies of the podium are the hotel lobby, laundry, restaurant, gym, ballroom, several conference rooms and small offices as well as a coffee shop and a bar.

The common areas are conditioned through a total of 14 air handling units (AHU). These units are equipped either with a chilled water cooling coil connected to a central chiller plant or a DX (direct expansion) cooling coil, and with an electrical heating coil. The fans of the constant-volume system run 24 hours a day continuously.

The guestrooms are equipped with packaged terminal heat pumps (PTHP) with cycling fans to meet the heating and cooling load, respectively. The set point temperatures can be changed by the guest. Exhaust air is extracted through the bathrooms operated with one common rooftop fan per riser.

In general, the main energy source for the conditioning of the hotel building is electricity. Gas is used only for service hot water (SHW) generation as well as for the laundry and kitchen equipment.

The simulation tool used to carry out the calibration was EnergyPlus v4.0 (U.S. Department of Energy).

MONITORING

To get a detailed insight into the building operation the hotel was outfitted with wide-ranging monitoring equipment. Since the whole building electricity and gas meters are the only existing source for information regarding the energy consumption of the hotel, the monitoring equipment was mainly used for the calibration of the individual systems. In addition, to the technical equipment, the outside air temperature was also monitored on site and used in the calibration in conjunction with the weather data of 2009.

Guestrooms

Given the situation of more than 300 guestrooms in total it is not economically feasible to outfit every single room with the necessary monitoring equipment. Instead, a sample of guestrooms was defined to represent the total. In order to be representative, 32 rooms were equally distributed among the tower in terms of orientation, height, and location (corner room or center room).

In each guestroom the following parameters were monitored (see also Figure 2):

- PTHP Total electricity consumption
- PTHP Supply air temperature
- PTHP Return air temperature
- Electrical equipment (e.g. TV, Refrigerator)
- Lighting

![Figure 2: Guestroom PTHP unit equipped with data loggers](image)

These five data points sufficiently covered the energy consumption of the guestrooms.

Common Areas

Each individual AHU is included in the monitoring plan; however, due to limited accessibility not every AHU could be outfitted with the same metering points.

In general, the installed data points for the air handling units are:

- AHU Supply fan electricity consumption
- AHU PreHeater electricity consumption
- AHU ReHeater electricity consumption
- AHU Supply air temperature
- AHU Mixed air temperature
- AHU Return air temperature
- AC (Air conditioning) Electricity consumption (3 out of 14)

However, detailed monitoring including temperature measurements was applicable for only four out of the fourteen AHUs; for the remaining units only the supply fan and the electrical heater were monitored. In addition, the central chiller plant was equipped with metering points.
Detailed information about plug loads and internal gains was made available through measurements in the common areas as well as in more specific types of use like the laundry and the kitchen. This ranges from lighting circuits and vending machines to washers and walk-in coolers.

Gas

As mentioned at the beginning service hot water is generated by gas-fired storage tanks. Additionally, natural gas is used in the laundry for the clothes dryers and ironer, as well as for various cooking appliances in the kitchen. Since the metering of each device was not possible due to high costs and complexity, it was decided to meter only the central service hot water equipment and the laundry equipment; kitchen cooking appliances are assumed to be the remaining difference to the total gas consumption.

Dealing with Monitoring Data

As well as the installation of more than 400 data points there is also a data collecting process. Downloading the data from every logger takes two people two full days. In public areas the monitoring equipment was mostly hidden in order not to influence the user’s behavior. This resulted in a complicated access to the monitoring equipment. Additional difficulties included data logger removal or the devices that have been discovered by a guest were unplugged. Nevertheless, a significant amount of data over a time span of three months from September to December was gathered.

Analysis of Monitoring Data

Within the calibration process, monitoring data is used in two different ways:

a) As an input for the actual model that is processed in the calibration runs as consumer and internal gains. This concerns lighting and electrical equipment such as vending machines, TVs or refrigerators.

b) For comparison to the simulation outputs in the calibration procedure. This includes the electricity consumption of PTHP units, the AHU supply fans, electrical heater, and AC.

In both cases the accumulated data needed to be verified and analyzed. For this purpose, the PIA-tool was used (Baumann et al., 2004; Isakson, 2003, 2002). It is capable of visualizing huge amounts of data in form of carpet and scatter plots. Thus, allowing the user to compare various data points of a longer monitored period, and also, for a more detailed insight, to analyze the dependencies of these data points. For example, some PTHP units were refurbished, during this process data loggers were removed from the unit but still continued to record data. Since the values of this time period are out of the regular limits, these data could be spotted and excluded. Additionally, the verification demonstrated the variety of the guestrooms in terms of the room set point temperatures and the corresponding PTHP electricity consumption. Figure 3 demonstrates the outputs from the PIA-tool. Shown is the PTHP electricity consumption plotted against the supply air temperature with the values for heating and cooling operation colored in red and blue, respectively. The left chart illustrates the closeness of the heating and cooling operation and therefore the user influence. In contrast, the right chart is an example for a distinct heating and cooling operation. With respect to the calibration, these findings led to the conclusion that the guestroom data had to be simplified.

Data Implementation

All available data that were used as input in the simulation model was aggregated in 24hr profiles and then directly implemented in the according zone of the EnergyPlus model. For the 270 not monitored rooms, three statistical profiles were derived from the measured data and were used in the model.

With the purpose to reduce the calculation time of the simulation, several simplifications, e.g. in the thermal zoning, were made (see Figure 4).

![Figure 3: Two PTHP units: Total Electricity Consumption PTHP vs. Supply Air Temperature](image)

![Figure 4: Zoning of typical guestroom floor plan](image)
Thus, not every profile could be implemented in the model and the monitoring data had to be compared to each other. Figure 5 demonstrates exemplary the comparison of available profiles for one zone with the crossed line being the chosen one. The analysis revealed that for different monitored guestrooms the pattern of the profiles were similar.

In this assessment, line charts of the hourly data points plotted against sorted outside air temperature were found most useful.

Since the simulation model uses simplified controls that imitate the function of the actual controllers, it would be very time consuming and inefficient to match the simulated energy consumption exactly to the measured consumption. Instead, trend lines, based on the hourly line plots, were used. They are accurate enough to derive the characteristics of the energy consumption and thus, sufficient for the calibration.

To visualize the actual deviation of simulated to measured data, calibration signatures (Wei et. Al., 1998) were used and plotted as a scatter plot in conjunction with simulated and measured consumption against outside air temperature:

\[
\text{Deviation} = \frac{-\text{Residual}}{\text{Max. Measured Value}}
\]

where \( \text{Residual} = \text{Simulated Value} - \text{Measured Value} \)

Furthermore, to have in addition to the calibration charts also comparable quantities available the following indicators were also included:

- Percentage difference of the total energy consumption over that monitoring period
- Average hourly deviation
- Standard deviation
- Root Mean Square Error
- Mean Bias Error

The Root Mean Square Error (RMSE) is defined as follows (Bensouda, 2004):

\[
\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (\text{Residual}_i)^2}{n}}
\]

where \( n = \text{number of data} \)

The Mean Bias Error (MBE) is defined as follows (Bensouda, 2004):

\[
\text{MAE} = \frac{\sum_{i=1}^{n} \text{Residual}_i}{n}
\]

where \( n = \text{number of data} \)

Both error indicators together give information about the variation and bias of the simulated data compared to the measured data. Whereas the RMSE is more a sign of the magnitude of the error, the MBE indicates whether the simulation systematically overestimates or understimates the measured energy consumption.
of large errors, the MBE gives information about the overall distortion of the simulation results compared to monitored data.

All of the above mentioned evaluations which were performed after each calibration run, are combined in one single page for a fast and easy comparison.

In general, the calibration was carried out in two main steps; first is the detailed calibration of the individual systems based on available monitoring data which was then in a second step validated for the whole year.

**Individual Calibration of Guestrooms**

The first calibration runs focused on the heating operation of the PTHP units. For that reason a cold month with low outside air temperatures was chosen. The monitored return air temperature which is equivalent to the room air temperature was used as a continuous set point temperature.

In the first individual comparison of the PTHP electricity consumption, the simulated and monitored guestrooms values for MBE\textsubscript{RAT} were within a range of -0.0028 to +0.0084 °F, very small. This result indicates similar thermal conditions in the model compared to the real world situation. However, due to a wide variance in the PTHP characteristics it became apparent that the influence of the user was not the only disturbance value for the calibration. In fact, the solar radiation proved to be a major disturbance factor. This had a strong impact on the ability to calibrate the PTHP systems. In addition, the infiltration rate, specified as DOE-2 default value, is equally defined for all zones. However, because it is dependent on the wind velocity this results in different impact intensities for the various orientations. Therefore, the next step intended to minimize the impact of these disturbance factors. Thus, zones that experienced similar effect of these factors were grouped together and calibrated separately. Fortunately, the direction of the building follows a strict north-south orientation which made this effort relatively easy.

The initial run performed for the north-orientated guestroom group had again a very small MBE\textsubscript{RAT} of +0.0165 °F. The trend line characteristic of the PTHP electricity consumption was already relatively close to the monitored values in terms of the shape what proved the applicability for grouping the guestrooms. Deviations between the simulated and the measured energy consumption of the PTHP unit were now primarily due to differences in the performance specifications of the units. For that reason, adjustments in the COP value and the corresponding performance curve were necessary to get closer to the monitored electricity consumption.

After the calibration of the heating operation based on the north-orientated guestrooms, the altered parameters had to be applied and validated also for the south-orientated guestrooms.

The results of the heating calibration are shown in Table 1 together with the initial values before the calibration.

**Table 1: North-orientated Guestroom PTHP Heating Calibration Results – Simulation Period: mid-November to mid-December 2009**

<table>
<thead>
<tr>
<th>Type</th>
<th>Initial</th>
<th>Calibrated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity Consumption</td>
<td>-35.3 %</td>
<td>-2.4 %</td>
</tr>
<tr>
<td>RMSE\textsubscript{el}</td>
<td>+0.2450 kWh</td>
<td>+0.1785 kWh</td>
</tr>
<tr>
<td>MBE\textsubscript{el}</td>
<td>-0.1389 kWh</td>
<td>-0.0095 kWh</td>
</tr>
<tr>
<td>Electricity Consumption</td>
<td>-20.6 %</td>
<td>+5.1 %</td>
</tr>
<tr>
<td>RMSE\textsubscript{el}</td>
<td>+0.2851 kWh</td>
<td>+0.2624 kWh</td>
</tr>
<tr>
<td>MBE\textsubscript{el}</td>
<td>-0.1425 kWh</td>
<td>-0.0654 kWh</td>
</tr>
</tbody>
</table>

For the north-orientated guestrooms the simulation has a lower energy consumption than the monitoring data whereas the simulated south-facing group is higher. This result confirms the impact of the solar radiation.

In order to achieve an even more accurate calibration of the guestrooms it would be necessary to account for all the various effects of the solar radiation in the simulation model. For example, a layer of higher temperature on the façade caused by high irradiation affects the condensing unit as well as the outside air intake of the PTHP unit. The temperature layer varies for different floors and orientations. Therefore, a separate outside air node would be necessary for each PTHP unit. This would require detailed information about solar radiation and the situation in terms of the shading caused by surrounding buildings. For a practical calibration approach, though, the achieved accuracy is sufficient.

To be able to conduct the calibration of the cooling operation, monitoring data with higher outside air temperatures was necessary. Since the monitoring data available began in September, the cooling operation was calibrated using the first four weeks of monitoring data. As already observed for the heating calibration, with the monitored return air temperature as the room set point, the general shape of the electricity consumption matched the monitoring data relatively well. Therefore, modifications of the COP and the corresponding performance curve led to the results shown in Table 2.
### Table 2: Guestroom PTHP Cooling Operation Calibration Results – Simulation Period: September 2009

<table>
<thead>
<tr>
<th>O</th>
<th>TYPE</th>
<th>INITIAL</th>
<th>CALIBRATED</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>Electricity Consumption</td>
<td>- 30.6 %</td>
<td>- 5.8 %</td>
</tr>
<tr>
<td></td>
<td>RMSE(_{el})</td>
<td>+ 0.1084 kWh</td>
<td>+ 0.0160 kWh</td>
</tr>
<tr>
<td></td>
<td>MBE(_{el})</td>
<td>- 0.0518 kWh</td>
<td>- 0.0098 kWh</td>
</tr>
<tr>
<td>S</td>
<td>Electricity Consumption</td>
<td>- 32.3 %</td>
<td>- 7.0 %</td>
</tr>
<tr>
<td></td>
<td>RMSE(_{el})</td>
<td>+ 0.1438 kWh</td>
<td>+ 0.1326 kWh</td>
</tr>
<tr>
<td></td>
<td>MBE(_{el})</td>
<td>- 0.0765 kWh</td>
<td>- 0.0165 kWh</td>
</tr>
</tbody>
</table>

### Individual Calibration of Common Areas

The calibration of the AHUs consisted of the supply fan, the electrical heater and the AC. The AHUs serve mostly internal zones where solar radiation has no impact; therefore, a different approach for the calibration was necessary. Because of variations in occupancy types, occupancy times and size, it was not possible to combine the units as it was done for the guestrooms. In addition, the fact that the podium was remodeled several times in the past led to vagueness in terms of the current placement of the ductwork and information about the air flow rates. Therefore, the input for the initial simulation was a combination of theoretical calculations (e.g. pressure drop), information from the original drawings, and information from the technical staff on site. For example, the personnel provided essential insight into the technical condition and position of the outside air dampers; e.g. most of the dampers were defective and fixed in either open or closed positions.

The initial calibration run of the AHUs disclosed that the simulated supply fan electricity consumption was, both too high and too low. This deviation could be adjusted by modifying the fan efficiency and the system’s pressure drop. The refurbishment of the building systems did not include a replacement of the constant-volume fans. Therefore, an adjustment of the corresponding flow rates, which were initially based on design values, was done only when necessary.

Regarding the electrical heater, the simulated consumption in the initial calibration run was in some cases more than six times higher than the measured values. These results indicated that the specified outside air flow rates based on the design had to be modified due to the malfunctioning outside air dampers. In fact, the flow rates were reduced by 54 to 100 % in the calibration process to meet the monitored electricity consumption.

Additionally, information regarding internal gains was not available for all systems. Since these loads can vary significantly depending on occupancy and use, the absence of this information made the calibration of some AHUs problematic.

During the calibration process it became apparent that the monitored data was in some cases not correct. For instance, one electrical heater indicated no heating operation at all according to the monitoring data. However, given the circumstances of the conditioned area, it was certain that heating was required to meet the set point temperatures. Verification with the technical staff confirmed the value of the room temperatures and led to the conclusion that the conversion of sensor impulses to electricity was not correct.

After a maximum of about five calibration runs every AHU was calibrated; Table 3 summarizes the results of these calibration efforts. The results for both the supply fan and the electrical heater demonstrate a large improvement in terms of the convergence of the simulated data to the measured data.

The results of the AC calibration reflect the lack of monitoring data with higher outdoor air conditions and cooling operation.

### Table 3: AHU Calibration Results – Simulation Period: mid-September to mid-December 2009 (varies depending on AHU)

<table>
<thead>
<tr>
<th>TYPE</th>
<th>INITIAL</th>
<th>CALIBRATED</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity Consumption</td>
<td>+ 21.9 %</td>
<td>+ 0.2 %</td>
</tr>
<tr>
<td>RMSE(_{el})</td>
<td>+ 0.9605 kWh</td>
<td>+ 0.3722 kWh</td>
</tr>
<tr>
<td>MBE(_{el})</td>
<td>- 0.5241 kWh</td>
<td>- 0.1112 kWh</td>
</tr>
<tr>
<td>HEATER</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity Consumption</td>
<td>+ 395.3 %</td>
<td>- 16.8 %</td>
</tr>
<tr>
<td>RMSE(_{el})</td>
<td>+ 16.9149 kWh</td>
<td>+ 7.6154 kWh</td>
</tr>
<tr>
<td>MBE(_{el})</td>
<td>+ 12.1263 kWh</td>
<td>- 1.0178 kWh</td>
</tr>
<tr>
<td>AC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity Consumption</td>
<td>- 13.8 %</td>
<td>- 7.6 %</td>
</tr>
<tr>
<td>RMSE(_{el})</td>
<td>+ 3.8582 kWh</td>
<td>+ 3.8699 kWh</td>
</tr>
<tr>
<td>MBE(_{el})</td>
<td>- 0.1487 kWh</td>
<td>+ 0.1258 kWh</td>
</tr>
</tbody>
</table>

1 Values are weighted based on system air flow rates

Unfortunately, due to the available time span of the monitoring data from September through December, there was not enough data available for a calibration of the central chiller plant. Instead the input values for the simulation model were verified with the manufacturer and applied accordingly.

### Annual Calibration of Gas Usage

Since the gas consumption for the generation of service hot water and the operation of the laundry and kitchen equipment makes up only about 25% of the total energy...
consumption, the approach for the gas calibration was simplified.

The basis for the gas calibration comprised monthly utility bills for the whole building gas consumption and monitoring data for some days in December. Since the utility bills demonstrated a direct relation of the gas consumption to the corresponding hotel occupancy, this information was used in the calibration process. In conjunction with the total occupancy of the hotel, adequate consumption profiles for SHW, laundry and kitchen equipment were created and adjusted to meet the actual gas consumption of the building. In this process it became apparent that the relationship between the gas consumption and hotel occupancy was not valid for hot summer months. In this case, the higher occupancy cancels itself out with a reduced demand in service hot water resulting in a relatively constant hot water demand. This was implemented in the model by adjusting the SHW profiles accordingly.

Overall, the calibrated gas usage had a difference of +2.5 % from the utility data.

**Annual Whole Building Calibration**

Once all the systems were individually calibrated based on monitoring data the adjustments were validated for a whole year for the entire building.

Due to the limited availability of monitoring data the monitored return air temperature used as the room set point had to be replaced with the previously mentioned 24hr temperature profiles. Since the continuous monitored return air temperature proved to be crucial for the detailed calibration, the use of these 24hr profiles seemed to lead to inaccuracies in the overall result. However, the annual electricity consumption deviation of -8.3 % was lower than expected. The following two graphs demonstrate the change in the characteristic of the total electricity consumption. Figure 6 illustrates the differences between the total electricity consumption and the utility data before the calibration and Figure 7 shows the characteristic for the calibrated model. In Figure 7 it is clear that for the heating operation the simulated electricity consumption for the building matches very well with the utility data. For the cooling operation the lack of monitoring data during summer leaves uncertain results.

The results shown in Table 4 give, in addition to the charts, more quantitative information about the results. Furthermore, the table demonstrates the necessity to visualize the results.

The table suggests a more accurate initial model before the actual calibration. However, this is due to the fact that the surplus of electricity used for heating during cold outside air temperatures and the lack of electricity used for cooling cancel each other out. Therefore, the difference in total electricity consumption is only -0.7 %.

![Figure 6: Characteristic of Non-Calibrated Model – Hourly Total Annual Electricity Consumption vs. Outside Air Temperature](image)

![Figure 7: Characteristics of Calibrated Model – Hourly Total Annual Electricity Consumption vs. Outside Air Temperature](image)

<table>
<thead>
<tr>
<th>TYPE</th>
<th>INITIAL</th>
<th>CALIBRATED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Electricity Consumption</td>
<td>-0.7 %</td>
<td>-8.3 %</td>
</tr>
<tr>
<td>RMSE&lt;sub&gt;e&lt;/sub&gt;</td>
<td>+6.0675 kWh</td>
<td>+3.0690 kWh</td>
</tr>
<tr>
<td>MBE&lt;sub&gt;e&lt;/sub&gt;</td>
<td>-0.0035 kWh</td>
<td>-0.0407 kWh</td>
</tr>
</tbody>
</table>

Figure 8 illustrates the simulation results compared to interval utility data on a monthly breakdown. The non-calibrated as well as the calibrated model results are included in the chart. The findings made in Figure 6 and Figure 7 can be noted.
CONCLUSION

The calibration of the simulation model of the hotel building to the utility data for both electricity and gas, could be achieved with a high degree of accuracy.

Compared to the hourly electricity interval data of the year 2009 the simulation model has a difference in the total electricity consumption of only -8.3%. The summer, however, shows the highest deviation because of a lack of monitoring data. The gas calibration to utility data has a difference in the total gas consumption of 2.0% also within an accuracy of ±10%.

In most cases an adjustment in the systems efficiencies led to the desired accuracy in the simulation model. COP values for heating and cooling of the guestroom PTHP units were reduced by 30% and 20%, respectively. Besides the performance modifications, the calibration process revealed that outside air flow rates do not conform to the initial design any more and were reduced by 50-100%.

The input adjustments made reflect the quality and performance loss of HVAC equipment over the course of time.

From the example of this case study the following recommendations for an accurate calibration can be drawn for future projects:

- With the information of detailed monitoring data it was possible to conduct the calibration in the following two steps:
  1. Detailed calibration of similar /identical zones.
  2. Validation of altered parameters in an annual whole building calibration run.
- Minimizing the impact of disturbance factors such as solar radiation, infiltration and user influence is essential.
- Detailed information of the envelope is necessary.
- Measured data should include at least one month of heating and one month of cooling operation.
- Communication and exchange of information with on site engineering personnel is essential to implement the most current status in the simulation model.
- The simulation software has to be able to model HVAC systems on a very detailed level; access to various information (temperature, flow rate) throughout the system (e.g. nodes) is crucial for the calibration.
- The achievable quality of the calibration depends on the available data input.
- The calibration requires numerous simulation runs which makes a fast and organized post-processing of the simulation results necessary.

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