UTILIZING SENSOR TREND DATA TO OVERCOME THE CHALLENGES IN CALIBRATING A SIMULATION MODEL FOR MEASUREMENT AND VERIFICATION IN A NEW CONSTRUCTION PROJECT

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ABSTRACT

Context: Efficiency Valuation Organization (EVO) standardized the approach to Measurement and Verification (M&V) through the International Performance Measurement and Verification Protocol (IPMVP). One of the major hurdles for a project team adopting this approach to M&V for a new construction project is that the implemented controls for the facility may not align with the mechanical designer's intent. The project teams need to synergize the tasks related to Commissioning, M&V, Operations and Maintenance. Any "mis-implementations" of controls in the building identified during commissioning should be considered in the M&V process.

Aim: This paper aims to highlight the practical challenges in the M&V approach in a real life project. We propose the use of a quick visual approach to compare the controls design intent of mechanical designers to the actual implemented system controls to assist with energy model calibration in M&V process.

Methodology: A 5 story LEED Platinum certified office building was used for the study. Whole building calibrated simulation approach as defined by Option D in IPMVP volume III was used for M&V in the case study. The energy model for the building was created in EnergyPlus™ based on the as-built documentation and the energy usage from the meters of all the major systems in the facility was used to calibrate it. Initial comparisons of the energy performance of the simulation model and the actual building facility revealed major differences in the profiles of their energy usages. Commissioning tasks had revealed that the system was not functioning according to the design. These findings were used to make suggestions to the building engineer to optimize system operation and were also used for calibration of the energy model.

Results: Various parameters like the chiller schedules, hot water supply temperature set points, etc. were identified to be different from the project documentation and could only be identified from the sensor trend data. The conclusions highlight the lessons learnt and the importance of such an analysis in real-life projects.

INTRODUCTION

Energy simulation models have become an integral part of the mechanical design process. Simulation software are used at various stages like load calculations, design, design optimization, establishing baseline for existing buildings, calculating energy efficiency measure (EEM) savings, implementing model based predictive control etc. (ASHRAE, 2013) According to ASHRAE fundamentals handbook 2013, building performance models comprise of three components:

1. *Inputs variables:* They comprise of the variables related to desired system component set points, thermostats as well as the variables related to the weather conditions.
2. *System assembly and its components properties:* These are the performance specifications at the component level as well as the system level.
3. *Outputs:* These are the results from the simulations based on the inputs related to the thermal loads, mechanical systems and weather.

Calibration of building energy performance models generally require all these three model components to match the actual building systems. Calibrated energy models can be used to study various EEMs to improve the system performance (Raftery, 2011). Improving the accuracy of the components of the calibrated building energy models would imply an increased confidence in the EEMs that can be proposed to the buildings owners. Research by National Renewable Energy Laboratory (NREL) showed evidences of overprediction of energy usage by energy models due various inaccuracies in the models which points to a need to an approach to improve the accuracy of the energy usage and savings predictions (Polly, 2011). This paper presents an approach to synergize various project tasks to identify the deviations of the energy modeling inputs related to the implemented control strategies through visualizations. The suggested approach of operation diagnostics is presently used to identify functioning deviations of actual HVAC systems by comparing the building automation system (BAS) data to the sequence of operations (SOOs) from controls submittals.

CALIBRATION AND VALIDATION

Literature Review

In general, all energy models need validation of results but it is critical for calibration studies. Judkoff et al.(2008) state two approaches of validating energy simulation analysis:

1. Analytical analysis – detailed analysis of the model and its inputs
2. Empirical analysis – comparison of the model to the actual data

Much research has gone into improving the reliability of savings predictions of EEMs based on calibrated energy models. Much of this research focuses on comparison of the simulation outputs to the actual data collected from actual systems. Researchers such as Tabares-Velasco et al. (2012), Mateus et al. (2014), Raftery et al. (2011) have presented approaches to improve the acccuracy of calibrated models by statistical analysis of outputs and the actual data from the system functioning. The proposed approach delves into the analytical analysis of the implemented HVAC controls from the building to improve the accuracy of inputs related to the controls within the calibrated simulation.

Case Study

The energy model of a 5-storey office building located in Nürnberg, Germany was used as a case study for this paper. The building is LEED platinum certified. Meter data and BAS sensor trend data were used in the M&V process.

Figure1 shows the geometry of the energy model of the building. The building is conditioned by a direct outdoor air system and thermally activated slabs. Natural ventilation is used to meet the additional cooling loads during summer in the office spaces.

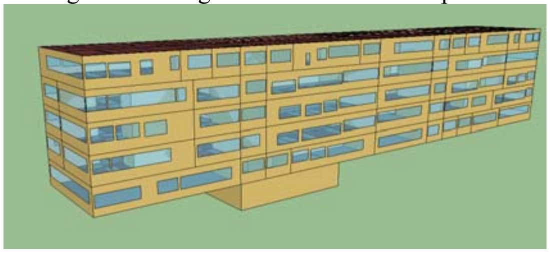

Figure 1Geometry of the Energy Model in OpenStudio Plugin for SketchUp

The zoning was based on the as-built architectural floor plans and all the energy modelling inputs were acquired from the as-built design documentation and the manufacturer specifications of the mechanical components. The thermostats and the system set point values were matched with the acquired BAS trend data. Schedules were created based on the interviews with the building operation personnel. The geometry was built in OpenStudio plugin for sketchup and the simulations were run on EnergyPlus™. Once the inputs were satisfactorily adjusted, the simulated energy performance was compared to the metered energy data from 12 months of operation. The model was calibrated using the approach described in Volume 3 of the International Performance Measurement and Verification Protocol (IPMVP) – Option D Whole Building Calibrated Simulation.

IPMVP

Energy and Atmosphere credit 5 for LEED version 2009 – Measurement and Verification suggests the use of two M&V approaches (IPMVP, 2006):

Option B: Energy Conservation Measure (ECM) Isolation

This approach is more applicable for projects that are interested in understanding the performance and savings achieved by specific ECMs. However, this approach may ignore the various interactions among different systems as only a few parameters are used for the M&V process.

Option D: Whole Building Calibrated Simulation

This approach may be used to analyse the overall energy performance of the building. A simulation model of the energy building with all its systems is created and calibrated using the meter data collected from the building. This approach takes various interactions among different systems within a building. For example, the impact of reduced lighting loads for a particular period of time on the heating loads of the building could be accounted for in this approach of M&V.

Considering the extent and complexity of the ECMs in this building, *IPMVP - Option D: Whole Building Calibration* was used to evaluate the performance of the building and its systems; results were calculated using *Savings Estimation Method 2*. Thereby, the metered post-construction energy use was subtracted from the energy use of the calibrated baseline model. The M&V plan was developed based on the design development phase documentation. A metering concept showing all the submeters was developed based on the design documentation phase for this project. The metering concept was used to correlate the meter data to the energy consumption breakdown from the simulation model.

The main energy sources employed by this project are electricity and district heating. Both energy types were to be metered by the utility provider on the whole building level. Furthermore, the energy consumption on the plant level and the system level were expected to be monitored using sub-meters within the building.

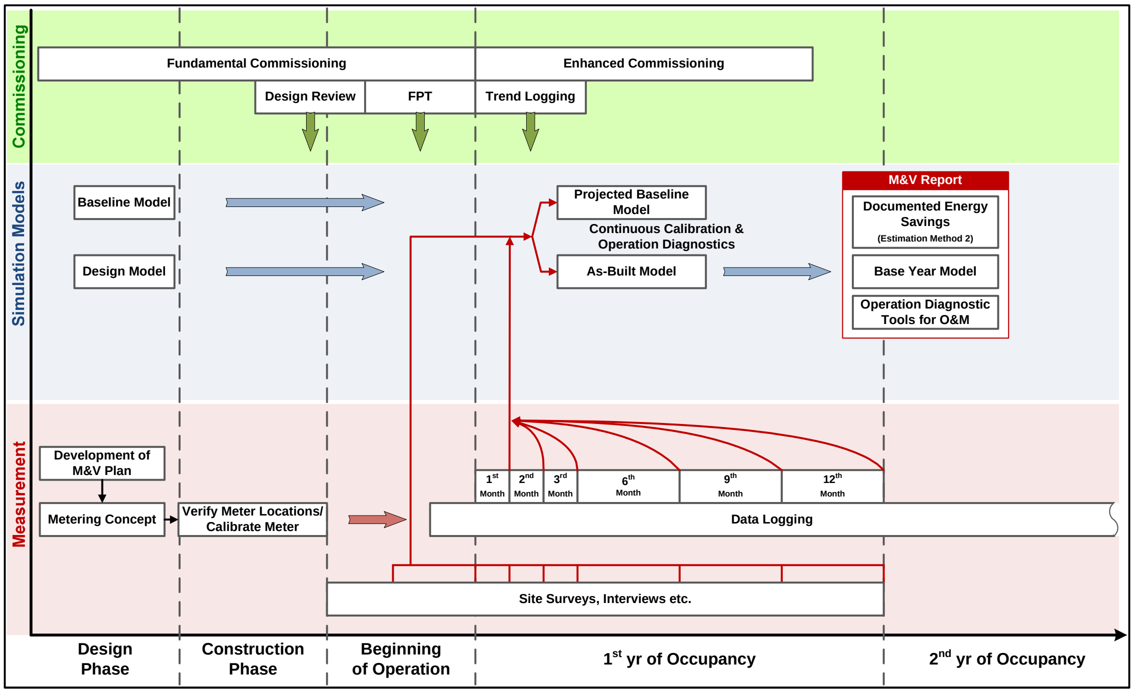

Figure 2 Flowchart depicting the M&V approach adopted for the casestudy

Sub-meters listed in the design documentation phase were as follows:

Total electricity consumption:

- Each individual office space (10)
- Cafeteria
- Common areas
  - Foyer
  - Staircases
  - Public restrooms
  - HVAC systems serving common areas
- Chiller plant
- Elevators
- Exterior areas

Total heating energy:

- District heating system
- Radiators North/South
- TABS North/South

Total cooling energy:

- Chiller cooling energy
- TABS North/South
- Server cooling coil

Based on the requirements outlined in IPMVP vol 3 for Option D – Whole Building Calibrated Simulation, savings calculation Method 2, the flowchart shown in Figure 2 was developed for the M&V approach. The commissioning tasks were further integrated into the M&V approach as shown.

The actual calibration followed the recommendations of ASHRAE guideline 14-2002, section 6.3. Calibration accuracy was calculated using the statistical indices MBE (Mean Bias Error) and CV(RMSE) (Coefficient of Variance of the Root Mean Squared Error) with anticipated accuracies for MBEs of ±10% and CV(RMSE)s of ±30% for hourly data or ±5% and ±15% when monthly data is being used. *EnergyPlus Version 7.2* software was used for modeling the building. Based on the design development phase documentation, the building was to be outfitted by its own weather station in order to control the exterior shading devices. The primary weather data for the calibration model were used from this weather station located at the building site. Missing weather information was acquired from the local weather station of German Weather Service (DWD) for the calibration of the energy model. The differences in the on-site weather station and the DWD weather data is critical for the calibration process. The project team used the DWD weather data for missing weather parameters for lack of accurate and complete weather data collection from the building. The simulation inputs of the proposed design model were adjusted to reflect the conditions of the building's operation during the M&V period. These changes consisted of updated internal gains (people, lights & electric equipment), operation schedules as well as performance specifications that had changed during the building operation.

As a part of the calibration process, the energy consumption from the actual building was first compared to the energy consumption of the simulated model for an initial analysis. This showed major difference in energy usage and hence it was further investigated.

Observations from the Initial Analysis

The calibration of the energy model was done after 12 months of meter data for the building functioning was available. Table 1 lists all the meters that were available for the M&V process and the observations from the preliminary comparison of the meter data to the calibrated energy model performance. It may be noted that the list of meters at this phase is different from the design development phase documentation. The M&V plan and metering concept were updated accordingly.

Table 1Observations from the initial comparison of the meter data and energy model performance

METER/SUB-METER	OBSERVATIONS
Overall Electricity Usage	The metered electricity usage of the building was much lower than the simulated electricity usage at the start of the time period but was more comparable for the last few months.
South wing Electricity Usage	The south wing electricity usage was much lower than the simulation model till October 2013 but sharply increased much above the simulated electricity usage after November 2013.
North Wing Electricity Usage	The north wing electricity usage was consistently lower than the simulated model.
Chiller Electricity Usage	• The chiller electricity usage was much lower than the simulated model before October 2013. The chiller electricity usage was much more comparable to the simulation model after October 2013. • The chiller electricity usage was much lower than the simulated model for the months of September and October 2013.
BAS Electricity Usage	• Sum of the energy usage by the BAS and the rest of the sub-meters was almost equal to the overall electricity usage by the building. • The BAS electricity usage was compared to the difference of the total model electricity usage and the other sub-meters. The difference was much higher for all months except for July and August 2013.
District Heating Usage	• The profile of usage of energy from district heating is comparable to the results from the energy model. • The metered district heating usage was greater than the simulation results till November 2013 and was lower after that.

Figure 3 shows the comparison of the measured and simulated whole facility electricity consumption. As noted in Table 1, the electricity usage for the actual building is much lesser than the simulated model for the first 7 months of operation. Differences in the simulation results and the meter data could be due to several factors such as – occupancy, schedules, varying internal loads, weather, etc. In addition to these, the commissioning activities observed a deviation of the system operation from the controls design intent. To understand the effect of these deviations of system operation on the energy consumption, the team analysed the BAS sensor data. An approach called Operation Diagnostics that visually analyses sensor trend data was used for this purpose.

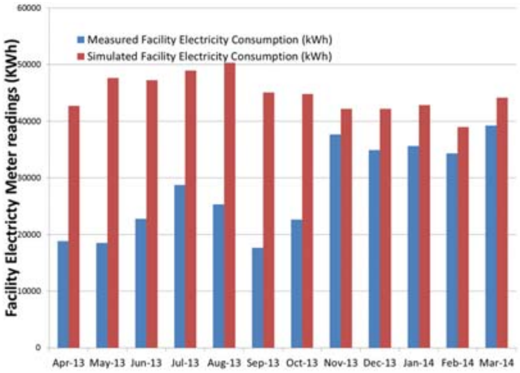

Figure 3Measured vs Simulated Whole Facility Electricity Consumption

<u>OPERATION DIAGNOSTICS</u>

Concept

Operation diagnostics is a visual approach to analyze the BAS trend data collected from an operating system by comparing it to the actual design specifications. Standard operation patterns are created from the system SOOs from the controls submittal. (Baumann, 2004)

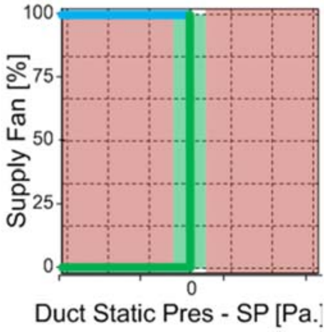

Figure 4 Operation pattern to represent the control of the duct static pressure at its set point by the supply fan

Figure 4 shows an operation pattern that was generated to represent the relation of the supply duct static pressure with the supply fan power. Green colored area represents the expected pattern of this control relationship based on the SOOs. The supply power modulates from 0% to 100% to maintain the duct static pressure at the setpoint value. The duct static pressure may fall below setpoint value when the fan is switched off. Blue color represents the area where the relation between the static pressure and fan pressure is functioning as expected but there could be a deviation else where in the system functioning. The red portion represents the area which would be considered a deviation from the SOOs. These operation patterns are created to correspond to each of the control sequences described in the SOOs.

The BAS sensor data corresponding to each of the combinations is then plotted against each other to visualize the pattern corresponding to the control that is implemented in the system. This is visually compared to identify any deviations from the ideal operation pattern during the commissioning of HVAC systems. A detailed description of this deviation analysis approach was presented in a previous study by Sunnam et. al (2015). The visualization of the BAS sensor trend data is done using a Matlab based tool named Pia. Figure 5 shows the plot of fan power vs the duct static pressure corresponding to the operation pattern in Figure 4.

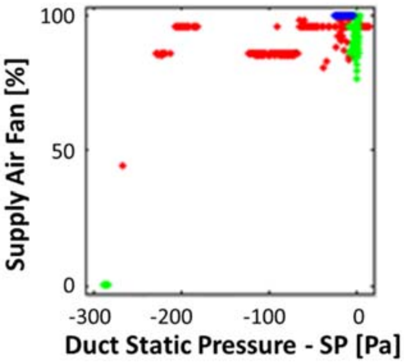

Figure 5 BAS sensor data for the supply fan power vs the difference of supply air pressure and its setpoint

In addition to scatter plots, Pia tool is also capable of producing carpet plots to visualize large amounts of data in a small amount of space to understand the operation schedules of a component. As shown in Figure 7, they represent the values in the form of colour maps and represent 24 hours of a day on Y-axis and all the days analysed on X-axis. The light blue coloured area in the carpet plots corresponds to missing BAS data. The initial analysis compared the carpet plots of all associated parameters from BAS data to the observed energy consumption trends.

Comparison of the energy consumption and the BAS trend data

It should be noted that the lack of ways to accurately document the precise functioning of the facility results in some limitations in modeling the exact as-is conditions. The comparison of design intent and BAS data was only used to make observations and pose retrospective questions about the usage of the building. These visual comparisons were very effective to communicate with the building operations managers. These retrospective questions pointed to the anomalies in the functioning of the building systems. Although the simulation model does not precisely match the as-is conditions at the building, the energy usage profile comparisons give valuable information about areas where the energy usage is much different from the designer's anticipated value. The observations from this report were used by the building manager to fine-tune actual system functioning and also by the M&V team to further fine-tune the energy model for calibration.

Chiller Electricity Usage

The profile of the chiller electricity usage appeared to align with the simulated chiller electricity usage after November 2013. Changes in cooling loads, occupancy or functioning of the building after October 2013 were verified to assess the change in the electricity consumption by the chiller based on these observations.

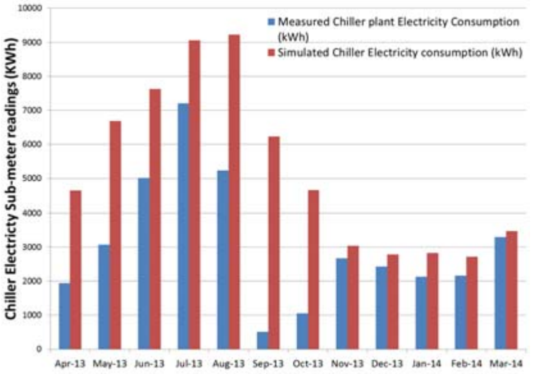

Figure 6Measured vs Simulated Chiller Electricity Consumption

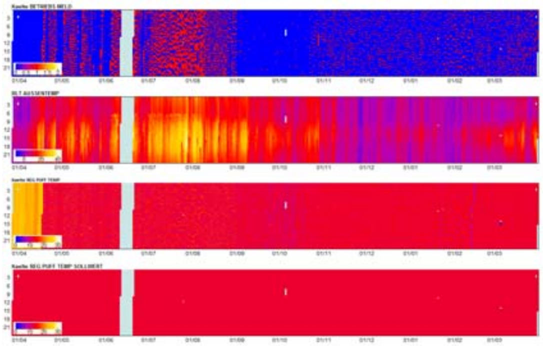

Figure 7 Carpet Plots (in order) (1) Chiller Operation, (2) Outside Air Temperature, (3) Chiller Supply Water Temp., (4) Chiller supply water Temp. Setpoint

As can be noted from the carpet plots, the chiller was being controlled based on the outside air temperature. By comparing the BAS trend data, it was clearly seen that the chiller had remained off for most of April, September and October. Hence actual chiller operation schedule was extracted from this BAS data to calibrate the energy model.

District Heating Usage

The metered data for months after November 2013 appears to be lesser than the simulation results. The heating energy received by the facility for the months of January, February and March 2014 was verified. Although the shape of the overall district heating energy usage matched the simulation results, anomalies were observed after November 2013.

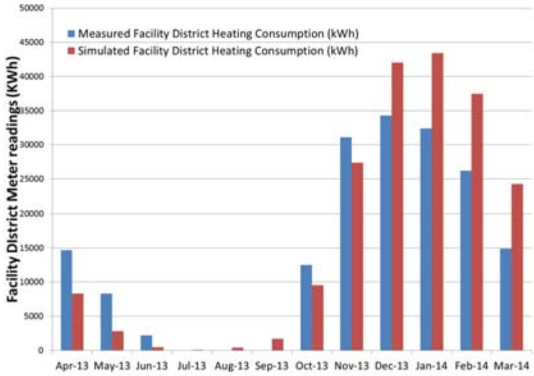

Figure 8 Measured vs Simulated District Heating Consumption

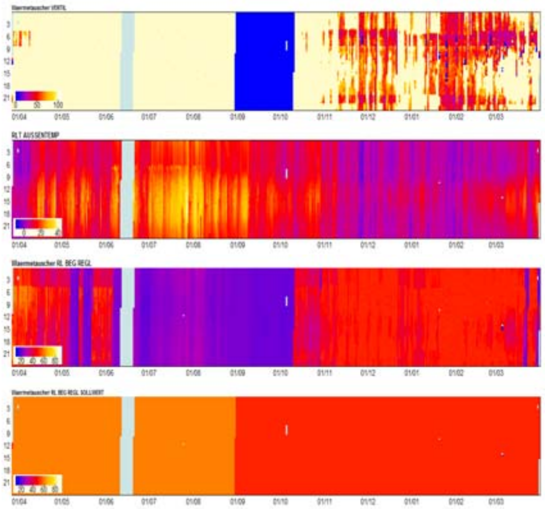

Figure 9 Carpet Plots (in order) (1) District heating supply valve, (2) Outside Air Temp., (3) District heating heat exchanger primary side return water temp., (4) District heating heat exchanger primary side return water temp. setpoint

As can be noted from the carpet plots, the primary side return water temperature setpoint was lowered in september. The district heating primary return water temperature was much lower than the setpoint between June and October which indicates that the system was not functioning for most instances during this period. Hence, the energy consumption was much lesser. It was switched on in October and the hot water supply valve modulated to maintain the supply water at its temperature setpoint. This led to higher energy usage after november 2013. Hence the supply hot water temperature setpoint in the simulation was adjsuted based on the observations from the BAS data.

STATISTICAL INDICES FOR CALIBRATION

The calibrated simulation model as an optimization tool during the operations and maintenance phase is valuable once it is adjusted to the conditions when the building is under optimal usage.

Once the optimal functioning of the facility is assessed, the simulation model inputs would be adjusted to reduce the statistical indices of Mean Bias error (MBE) and Coefficient of variance of the root mean squared error (CV-RMSE) as compared to the metered energy usage.

ASHRAE guideline -14 defines MBE and CV-RMSE as follows:

Mean Bias Error - MBE: The mean bias error is an indicator of how close the energy usage of the simulation model is to the actual metered data expressed as a percentage.

$$MBE = \frac{\sum_{i-1}^{n}(y_i - x_i)}{\sum_{i-1}^{n}(y_i)}$$

Coefficient of variance of the Root Mean Squared Error - CV(RMSE): The CV(RMSE) gives us an idea as to how well the simulation model fits the measured data.

$$CV(RMSE) = \frac{1}{\bar{y}}\sqrt{\frac{\sum_{i=0}^{n}(y_i - x_i)^2}{n}}$$

The variables used in the above two equations are:

n = Number of time steps (months in this case)
y_i = Measured energy consumption for the i^{th} time step
x_i = Simulated energy consumption for the i^{th} time step
$\bar{y}$ = Mean measured energy consumption

The calculated statistical indices during the preliminary analysis are shown in Table 2.

Table 2 Calculated statistical indices for all the meters

METER NAME	MBE	CV(RMSE)
Whole Facility Electricity Usage	-60%	69%
South Wing Electricity Usage	-8%	52%
North Wing Electricity Usage	-110%	112%
Chiller Electricity Usage	-71%	91%
BAS Electricity Usage	-128%	133%
Whole Facility District Heating	-12%	44%

According to ASHRAE Guideline 14(2002), whole building calibrated simulation performance path requires the computer model to have a MBE of 5% and CV(RMSE) of 15% to monthly metered data used for calibration. However, the monthly metered data may be used for calibration only once the building reaches its optimal functioning. This preliminary analysis is a qualitative analysis of the operation of the actual system against the design intent. The quantiative values extracted from the actual BAS data can further be used in the calibration of the simulation model inputs.

CONCLUSIONS

This paper presented the approach to analyse the actual building operation by comparing it against the mechanical design intent. The primary motivations of this analysis are as follows:

1. To qualitatively assess any anomalies in the facility functioning and to localize possible systems that are not functioning as anticipated
2. To provide the facilities management data to identify possible systems that need optimization to conserve energy
3. To introduce the identified system operational anomalies in the energy model for calibration

Deviations of the implemented controls from the design that were identified during commissioning tasks were observed to have a direct impact on the energy consumption of the facility. The simulation models can be accurately calibrated for this time period by comparing the sensor trend data using the approach presented in this paper. Future work would involve further calibration of the energy model to ensure that the statistical indices of calibration for the model are within acceptable limits.

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