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CALIBRATED SIMULATION MODELING FOR PERFORMANCE ANALYSIS IN BCVTB PLATFORM

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ABSTRACT

Building Automation System is used for operation, management, and control of building systems. Energy simulation modeling can be used as a tool to analyze the performance of buildings. This paper discusses how the Building Controls Virtual Test Bed (BCVTB) program can be used as a platform to link multiple programs and systems to generate and analyze the advanced building performance data. A real-time process of building commissioning and performance analysis, utilizing the BCVTB platform, is tested. Results are discussed in terms of pros and cons of this approach. Future development plans are proposed to improve the energy performance of buildings.

INTRODUCTION

Buildings are the main consumers of primary energy. In United States, buildings consume about 40% of total energy and more than two-thirds of the total electricity use. In order to minimize the energy consumption in buildings, optimal design, construction, operation and maintenance are all important.

Currently, there is a great deal of discussions about sustainability, green buildings, high-performance buildings, and/or energy efficient buildings. To achieve high-performance buildings, building practitioners are constantly trying to develop more energy efficient buildings while not compromizing human comfort. There are initiatives and challenges that have been set by both private and public sectors. The US Department of Energy (DOE) has come up with the Net-Zero Commercial Building Initiative (CBI), which strives to develop Net-Zero Energy Buildings (NZEBs) for commercial buildings by 2025.

Building Automation System (BAS) and Building Energy Management Systems (BEMS) are key technologies, since building owners/managers can achieve energy savings and energy efficiency goals for their buildings by utilizing these tools. These systems have become industry norms for the maintenance of high-performance buildings. BAS and BEMS are taking a vital roles these days as key information sources for building commissioning (Cx) and performance Measurement and Verification (M&V). Cx is a documentation process that ensures the building systems are designed, installed, and tested exactly to specifications and that they can be maintained and operated for performance as intended, and assures the efficiency of building systems, the proper training of building operators and the goal fulfilments of the owner's expectations (ASHRAE, 2005). To successfully perform Cx and performance M&V process for energy savings, a standardized technology, both cost and time-effective, is required. This should also integrate the data from existing BAS and/or BEMS systems as main part of the key evaluation parameters.

As new real-time commissioning and M&V technologies are developed, it is expected to achieve reduction of costs associated with the building commissioning processes and to maintain or improve the high performance level of buildings in real-time basis.

Many studies have been conducted for real-time co-simulation using BCVTB platform. Kwak et al. (2015) conducted real-time BEMS by using BCVTB platform integrated with EnergyPlus, Matlab, and EMCS for predicting building energy consumption. Pang et al. (2012) provided framework for real-time building performance assessment by using BCVTB integrated with BACnet and EnergyPlus to support the building operation and maintenance. When the platform is used for only one-year, there is no problem. However, if the platform is used for multiple years to achieve building energy consumption reduction goals, the platform has to be modified based on the newest real data. Most of the previous research is concerned about the real-data, which is used to calibrate simulation model, then predicted building energy consumption or found optimal building system control through the calibrated simulation model. But buildings do not operate in the conditions all the time. Buildings continually change their operations, schedules, or internal loads.

This study utilizes the BCVTB platform to compare between measured data of 2017 in a case-study building and the data generated from a simulation model. The simulation model was calibrated to the measured data of 2016 obtained from the case-study building. The automated re-calibration (or real-time calibration) process was conducted in the BCVTB platform.

RESEARCH OBJECTIVES

This study was to verify the method of real-time calibration using the BCVTB platform. In the previous research (Mirianhosseinabadi, 2016), a simulation model was calibrated using measured data and verified in the BCVTB platform using measured data of year 2016. However, this was not enough to say this platform is working correctly. Through this study, the BCVTB platform was verified using measured data of 2017 and compared with 2016 and 2017measured data.

The objective of this paper is to verify BCVTB platform developed for the case-study building and to prove that the calibrated simulation model, which had been verified using the 2016 measured data, can be used for real-time commissioning and can confirm if there are additional modifications necessary for future updates.

Also this study is to confirm if the building is working properly the way as it worked in previous year. If not, discussed will be on how this platform can be used in future conditions.

CASE-STUDY BUILDING DESCRIPTION

Figure 1 shows the case-study building. It is an office building in the RTP region of North Carolina. The building consists of a conditioned space of 4,273.5m^2 built in 2014. The three-story structure includes administrative offices, conference rooms, commons areas, a tissue archive freezer, archival gel storage, lectriver storage, and a data silo. (Mirianhosseinabadi, 2016).

This building was appropriate to implement the Real-Time commissioning and performance measurement and verification framework since this building is equipped with advanced BACnet compatible BAS and required meters to reasonably separate the building energy consumption from the entire campus.

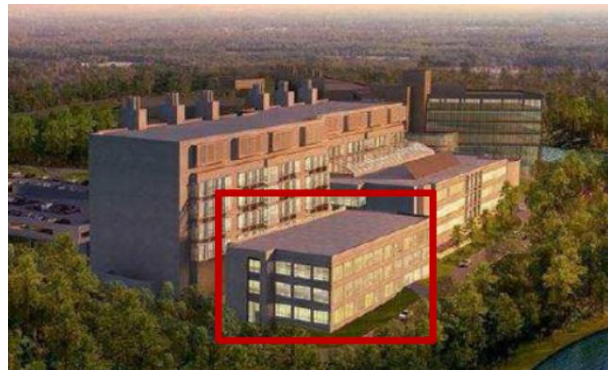

Figure 1 Case study building located in the RTP region of North Carolina

SIMULATION PROGRAMS

Building Controls Virtual Test Bed (BCVTB)

The BCVTB has been developed at the Lawrence Berkeley National Laboratory (LBNL) in 2008 based on the Ptolemy II software from UC Berkeley (LBNL, 2016). Ptolemy II is an open source software framework which supports experimentation with actor-oriented design (Ptolemaeus, 2014). Actors are software components that execute concurrently and communicate through messages sent via interconnected ports, and a Ptolemy II model is based on a hierarchical interconnection of actors. There are several programs and software that can be linked to the BCVTB (Figure 2) such as EnergyPlus, MATLAB, ESP-r, Radiance Analog/digital interface, and other computer language programs. To achieve the goal of this study, EnergyPlus, PostgreSQL, and Python are linked through BCVTB platform.

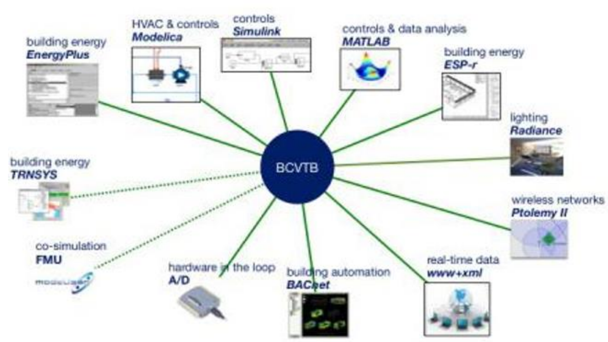

Figure 2 Programs that can be linked to the BCVTB (LBNL, 2013)

EnergyPlus

EnergyPlus program was developed by DOE in the mid-90s and is a simulation program that combines the advantages of BLAST and DOE-2 (U.S. DOE, 2017). The 8.8 version has been released recently since the first beta version was released in 1999. EnergyPlus program has already been designated as a simulation program for energy performance prediction when designing new buildings in the United States. For the load analysis, it uses the heat balance method which is recommended by American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) in United States. The reliability of the EnergyPlus program has been reviewed using Building Energy Simulation TEST (BESTEST) process of International Energy Agency (IEA). EnergyPlus program has been proven through many previous researches. This program is suitable to this study to calculate and predict building energy consumption and calibrate with real-building.

PostgreSQL

PostgreSQL is an open source relational database management system (DBMS) developed by a worldwide team of volunteers. PostgreSQL is not controlled by any corporation or other private entity, and the source code is available free of charge (Li et al., 2011). It can run on numerous platforms including Linux, Mac, Windows and others. PostgreSQL can make use of computer languages such as C++, Java, Python, Ruby, etc. to make database.

In this study, PostgreSQL is used to store measured data which is both transferred to the EnergyPlus simulation program and automatically compared with simulation results.

Python

Python is one of the programming languages. It has efficient high-level data structures and a simple but effective approach to object-oriented programming. The Python interpreter is easily extended with new functions and data types implemented in C or C++. Python is also suitable as an extension language for customizable applications. For this study, Python was used to provide intended messages to the users when the error rate between the measured data and the simulation data exceeds the specified error rate, which is preset in the BCVTB platform and shows the percentage of potential energy savings when the error is fixed.

SIMULATION MODELING

Calibrated simulation model

Figure 3 shows simulation model which is developed using SketchUp and OpenStudio plugin based on construction drawings. The simultion was carried out in EnergyPlus simulation program. Model calibration was done in the previous research (Mirianhosseinabadi, 2016). ASHRAE Guideline 14-2002 instructs building modelers to use monthly and hourly data, as well as spot and short-term measurements to calibrate BEM models. The guideline uses the Mean Bias Error (MBE) and Coefficient of Variation of the Root Mean Squared Error (CVRMSE) indices to represent how well a mathematical model describes the variability in measured data. “The computer model shall have an MBE of 5% and a CV(RMSE) of 15% relative to monthly calibration data. If hourly calibration data are used, these requirements shall be 10% and 30%, respectively” (ASHRAE, 2002). The value range of MBE and CV(RMSE) on hourly based analysis of this model was that MBE of 5.6% to 7.5%, and CV(RMSE) of 7.3% to 25.1% depending on the output variables which this paper covered. This result shows simulation model was calibrated successfully.

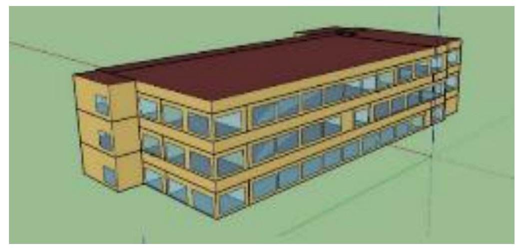

Figure 3 Geometry simulation model of case study building

BCVTB Platform

BCVTB platform was used to connect a calibrated simulation model (EnergyPlus) and measured data (PostgreSQL). Through this platform, simulated results and measured data were compared and analyzed in graphycal forms. The graphs were developed through the Python program, when the platform is run, the graph is generated automatically based on the simulation results and measured data.

The BCVTB platform consists of five main domains as follows:

- BCVTB model director
- EnergyPlus calibrated model inputs
- Building performance data
- Fault detection
- Real time and simulation time

BCVTB model director specifies the model of computation in the flow chart digram. EnergyPlus model calibrated using the 2016 measured data is used as calibrated model input. Building performance data is measured data which includes lighting electricity, equipment electricity, HVAC electricity, chilled water supply flow, and chilled water cooling energy. Fault detection starts with analyzing the difference between measured and simulated data for each performance metric in each step. However, this study does not deal with fault detection, since the goal of this study was to compare between 2017 measured data and simulated data to determine whether the initially calibrated model can be used in the later time. Real time and simulation time was used to show the time of data and bring the data and time into the Python codes for fault detection.

Figure 4 shows the internal structure of the BCVTB platform developed in this study. Through this platform, simulation results and measured data in 2016 were compared. A previous study was referred to verify this platform and simulation model (Mirianhosseinabadi, 2016).

This study used same platform as previous research, but this study inputs 2017 measured data in the building performance measured data part.

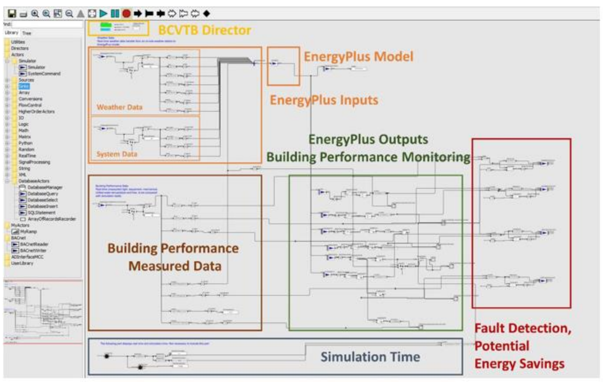

Figure 4 BCVTB platform main domains (Mirianhosseinabadi, 2016)

DATA ANALYSIS

Data analysis of 2017 year

During the process of collecting the measured data of the case study building, it was confirmed that the data collection device which is installed in the building was defective, the result of which was that complete data could not be collected. Both weather data and energy consumption are collected from July 4th to August 7th, 2017, a total of 35 days. Simulation model can generate many kinds of data with user's choice, but measured data is limited. Therefore, 4 types of data were chosen, which are included in both simulation and measured data. The 4 types of data are as follows:

- HVAC electricity consumption
- Chilled water flow
- Chilled water supply & return temperatures
- Chilled water cooling energy

Figure 5 shows the comparison of HVAC electricity between the measured and the simulation data from July 4th to August 7th, 2017. This was generated in the BCVTB platform directly. Two prominient results that can be seen here are; 1) actual HVAC electricity consumption is higher than simulation results by almost 10-30%, and 2) base loads of the measured data are lower than simulation results.

These result patterns are similar to those of the equipment electricity. The case study building opened in a few years ago, which means the operation of this building may change until fully occupied and operational. To confirm the differences, there is a need to double-check and confirm how HVAC electricity data is collected and which data is included.

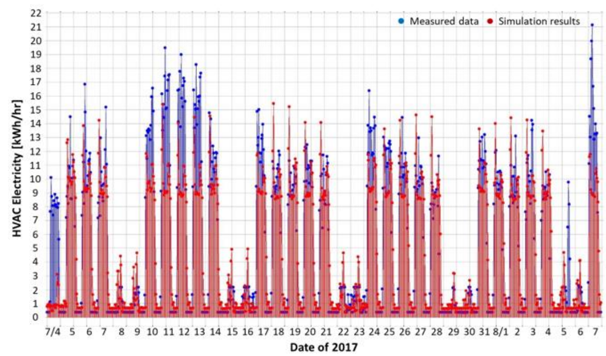

Figure 5 Comparison of HVAC electricity between the measured and simulation data

Chilled water supply flow and chilled water supply/return temperatures were collected in the case study building, but chilled water cooling energy data was not collected.

Therefore, the chilled water cooling energy was calculated using the following equation:

$$\text{Chilled water cooling energy} = \text{Chilled water supply flow} \times \text{water specific heat} \times \Delta T$$

Where,

Δ T: Return – supply temperature

The amount of cooling energy can be controlled by changing either flow rate or temperature. In this model, actual supply temperature is imported into EnergyPlus model to improve simulation accuracy. The measured data of chilled water supply flow in Figure 6 differs from simulation data, but Figure 7 shows the same. Because simulation run is based on the measured data; i.e. on chilled water supply temperature, which is why simulated data and measured data perfectly match.

In chilled water supply flow, the measured data and simulation data are similar to each other during daytime of the weekdays, but there is lower minimum supply flow than simulation in nighttime and the weekends when the building is not occupied. Therefore, it is considered necessary to change the value of minimum chilled water flow. Figure 8 shows that actual building used more cooling energy than simulation, almost 20-40% more, during daytime in weekdays.

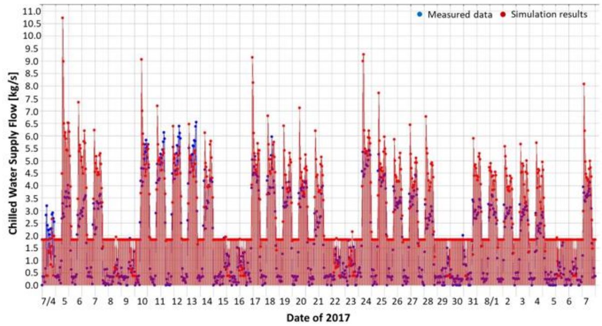

Figure 6 Comparison of Chilled water supply flow between the measured and simulation data

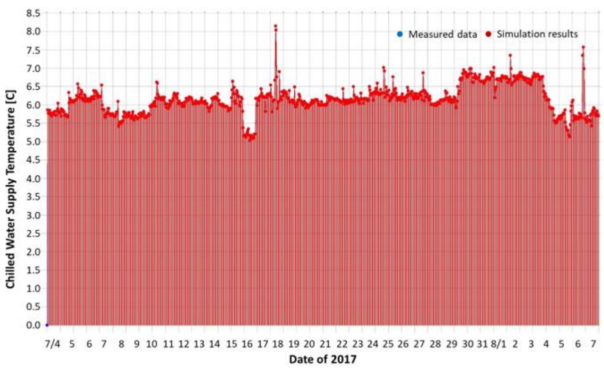

Figure 7 Comparison of Chilled water supply temperature between the measured and simulation data

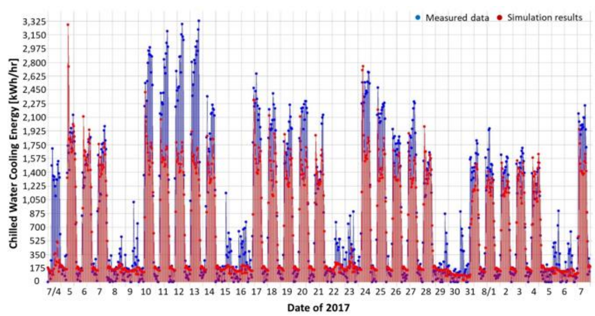

Figure 8 Comparison of Chilled water cooling energy between the measured and simulation data

Comparison of data of years 2016 and 2017

The analysis period in 2016 was July 2-6 and September 1-6. However, it was July 4-7 in 2017. Overlapping of the analysis period between 2016 and 2017 are July 4-6. Therefore, this study compares the data from July 4th to July 6th in 2016 and 2017. Even though the day of the week is different, this paper used same data for analysis. This is an office building, which means the schedules for weedays are similar. So, only weekdays and weekends or holidays were considered instead of individual days. This analysis is focused on comparing between 2016 and 2017. That is why this study choose overlapping period, and holiday and weekdays. Comparing the weather data can lead to more accurate energy consumption analysis.

Figure 9 and 10 compare two weather data factors that have a large influence on the indoor load and indoor condition, which are temperature and global solar radiation.

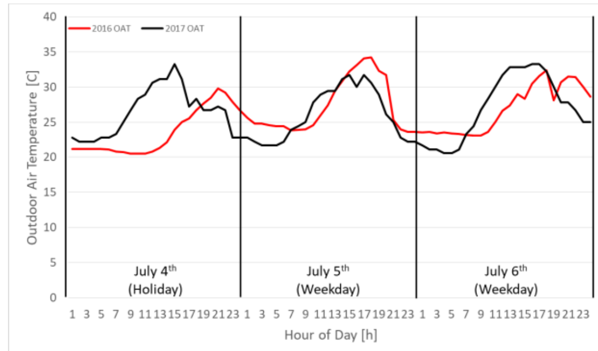

Figure 9 Comparison of outdoor air temperature between 2016 and 2017

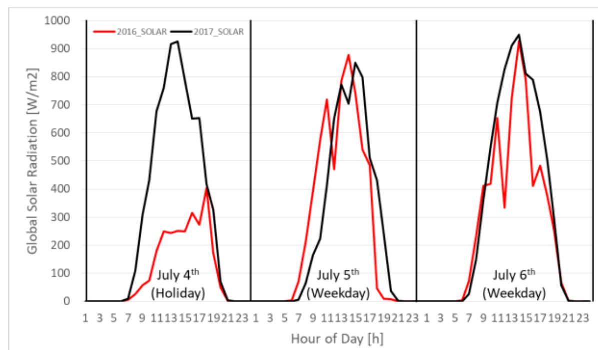

Figure 10 Comparison of global solar radiation between 2016 and 2017

On the July 4th, both outdoor air temperature and global solar radiation show a large difference. July 4th, 2017 appears to be warmer, since there is more solar radiation. On July 5th and 6th, there is a difference but it is not huge and all the data pattern is similar to each other.

For a weekday, the change of the indoor load or other electricity consumption is analyzed based on weather data difference, but the July 4th is a holiday in the United States, which means the case study building was not supposed to run with a weekday schedule but a holiday schedule.

Therefore, when analyzing the energy consumption of the July 4th, it is considered that the influence of the holiday makes it difficult to predict and analyze the building loads and schedules, and is more influential than the influence of the weather of that day.

On the July 5th and 6th between 2016 and 2017, the difference in weather data is not significant. If the difference of energy consumption of the July 5th and 6th between 2016 and 2017 is large, then it can be said weather is not the main reason for that difference. Hence, it can be predicted that the schedules of the building that have changed are more important reasons than difference of weather conditions, and analysis can be carried out on this basis.

Figure 11 shows the comparison of the HVAC electricity consumption between 2016 and 2017 year.

In Figure 5, in terms of the HVAC electricity, there was a big difference between measured data and simulation data from July 10th to 15th but not on July 4th to 6th. This comparison helps better understand data pattern, and see why there is a big difference. There is no big difference between measured data and simulation data from July 4th to 6th. July 4th is holiday in the United States, but both 2016 and 2017 showed huge discrepancies between simulation data and measured data because holiday schedule was used in EnergyPlus simulation program when in reality HVAC systems are working with weekday schedules, as it would during a weekday, on this day. The data of the July 5th and July 6th also show some differences, but data patterns seem to be similar. However, for 2017 data, HVAC electricity consumption increases slightly from 10 am to 12 pm. This pattern cannot be found in data of 2016. Therefore, actual behavior of the building at this time might be the reason rather than the error of the simulation. However, this is a speculation, so if there are any changes in the HVAC system, it needs to be updated in the simulation model.

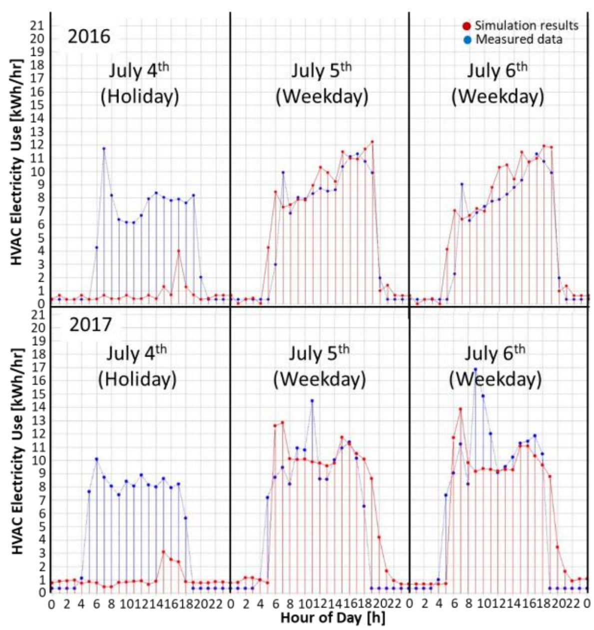

Figure 11 Comparison of HVAC electricity between 2016 and 2017

Figures 12 to 15 show the comparison of the chilled water supply flow, chilled water supply temperature, chilled water return temperature, and chilled water cooling energy between 2016 and 2017. Since the four results are related to one another, the analysis was carried out simultaneously. Figure 12 shows comparison of the chilled water supply flow. The simulation data do not differ significantly between 2016 and 2017. However, there is a difference in measured data. The data pattern is similar, but the data analyzed in 2016 seems to be a better match than the newly analyzed data of 2017. Looking at the newly analyzed data, 2 kg/s of minimum chilled water supply flow is steadily supplied at night when cooling is not required. However, the measured data is 0.5 kg/s of minimum chilled water supply flow. So the minimum chilled water supply flow for simulation model needs to be matched with actual building first. The chilled water supply flow is related to the chilled water supply temperature. The weather conditions are similar during this period and internal heat gains also match as shown above, which means the required amount of cooling energy could be similar in 2016 and 2017 data.

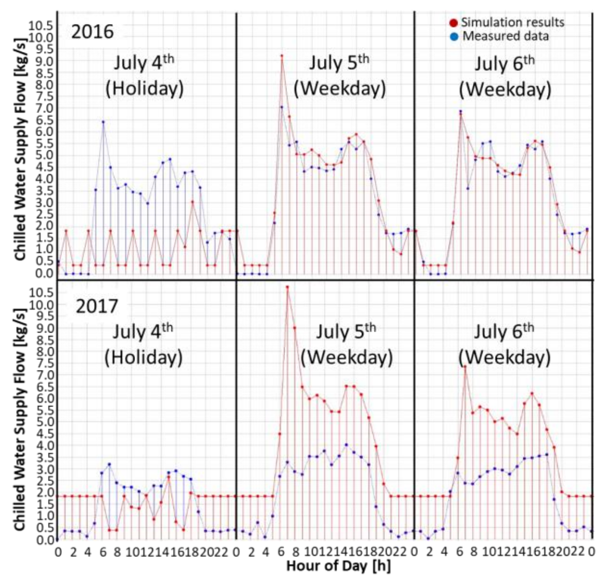

Figure 12 Comparison of chilled water supply flow between 2016 and 2017

As shown in Figure 13, the chilled water supply temperature in 2017 is maintained at around 6°C, and the chilled water supply temperature in 2016 was maintained at 6.7°C. To make clear, the chilled water return temperature of July 5th in 2016 and 2017 is compared as shown in figure 14. Figure 14 shows that chilled water return temperature in 2017 is higher than in 2016 from 12am to 10am, and chilled water return temperature in 2017 is similar with that of 2016 from 11am to 12am. As described above, since the chilled water cooling energy is not measured, it is calculated using equation as described earlier.

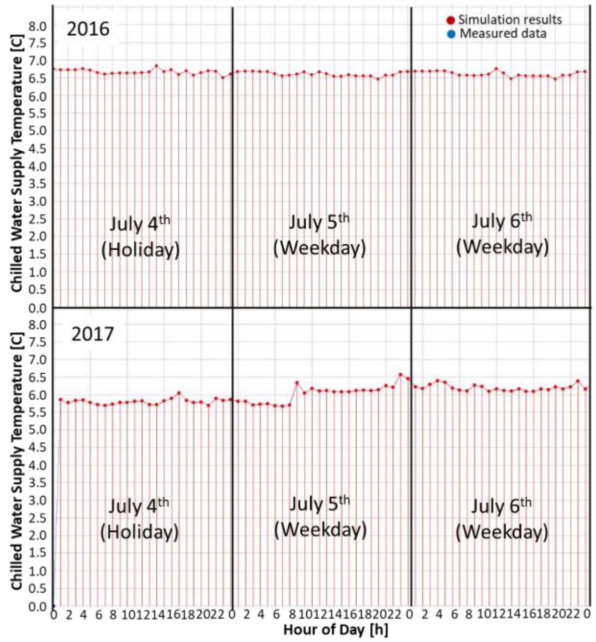

Figure 13 Comparison of chilled water supply temperature between 2016 and 2017

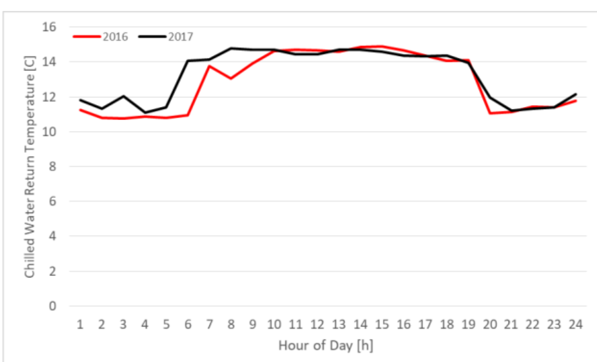

Figure 14 Comparison of chilled water return temperature between 2016 and 2017

Through Figures 13 and 14, it is calculated that ΔT for 2017 is higher than 2016, because supply temperature in 2017 is lower than 2016, and return temperature in 2017 is higher than or similar to 2016. When ΔT is large, chilled water supply flow is small, if cooling energy is similar.

Figure 15 shows that measured cooling energy for 2017 is similar in pattern and value with cooling energy for 2016. That is why chilled water supply flow for 2017 is lower than chilled water supply flow for 2016. Thus the measured data pattern is explained; however, the big difference between measured and simulation data at 7 am still cannot be readily explained. In order to reduce the gap, existing building and simulation model need to be double-checked and confirm the chilled water supply flow and chilled water cooling energy at 7 am.

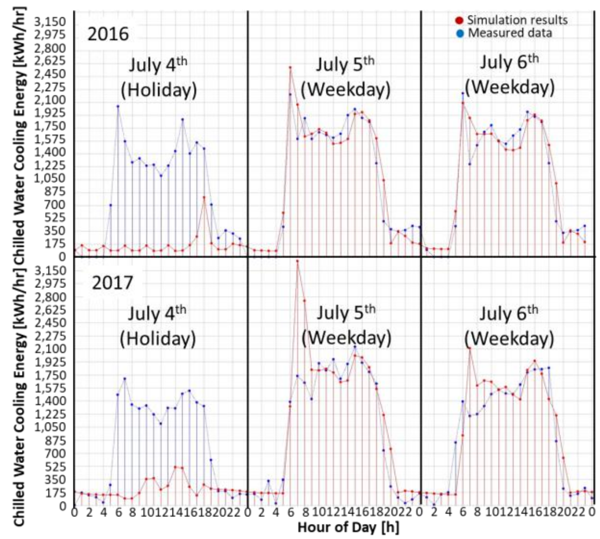

Figure 15 Comparison of chilled water cooling energy between 2016 and 2017

Pros and cons of using the BCVTB platform

As mentioned above the BCVTB platform can be used to automatically connect simulation model and real-time data and to simultaneously create graphs for visual representation, which makes it easier to visualize, understand and update data. This can save both time and manpower during the M&V processes. In this study, the simulation model was calibrated by using data from 2016, and this study confirms that the calibrated model shows similar energy use pattern in 2017. Weather affects heating and cooling energy, but operation of the building is also important. The pros of the BCVTB platform can be found through the results of this study, which are as follows:

- Many types of data can be analyzed at the same time.
- Results can be shown by graphs without additional works.
- Building conditions can be directly identified.
- Actual building energy consumption can be compared to the simulation data, and users can detect potential problems.

The cons of the BCVTB platform are as below:

- The simulation model calibration process needs a lot of time and manpower.
- The calibrated simulation model needs to be recalibrated periodically.

- Many sensors are required to measure the conditions of building performance.
- Database is required to store collected and processed data.

The BCVTB platform used in this study is strong in terms of linking multiple tools and systems for them to communicate one another; however, it still needs improvement in terms of ease of use.

In the future, other programs can be integrated in BCVTB to make better process and analysis between simulation and measured performances. The case study building is in operational since 2014. If BCVTB platform is used for newer buildings, simulation model needs to be calibrated. New building conditions need to be confirmed to provide accuarate comparison or control to improve building energy efficiency. When measured data from 2016 was used for calibration, the case study building was not fully operational, so the 2017 data has provided confirmation which part changed as compared to 2016, so that the initially calibrated model can be recalibrated with updated information.

CONCLUSION

This study was to see whether the initially calibrated simulation model can be used later to analyze the performance of a building by comparing the simulated results with measured data. A case study building was used to confirm the usefulness of the initial calibration model by comparing the data from 2016 and 2017 in a BCVTB platform .

Some advantages and disadvantages of the BCVTB platform are discussed. More simple and easy-to-use approaches are necessary for stake holders to better utilize the powerful functions of BCVTB.

In the future, a simplified calibration technology will be developed along with real-time weather access.

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