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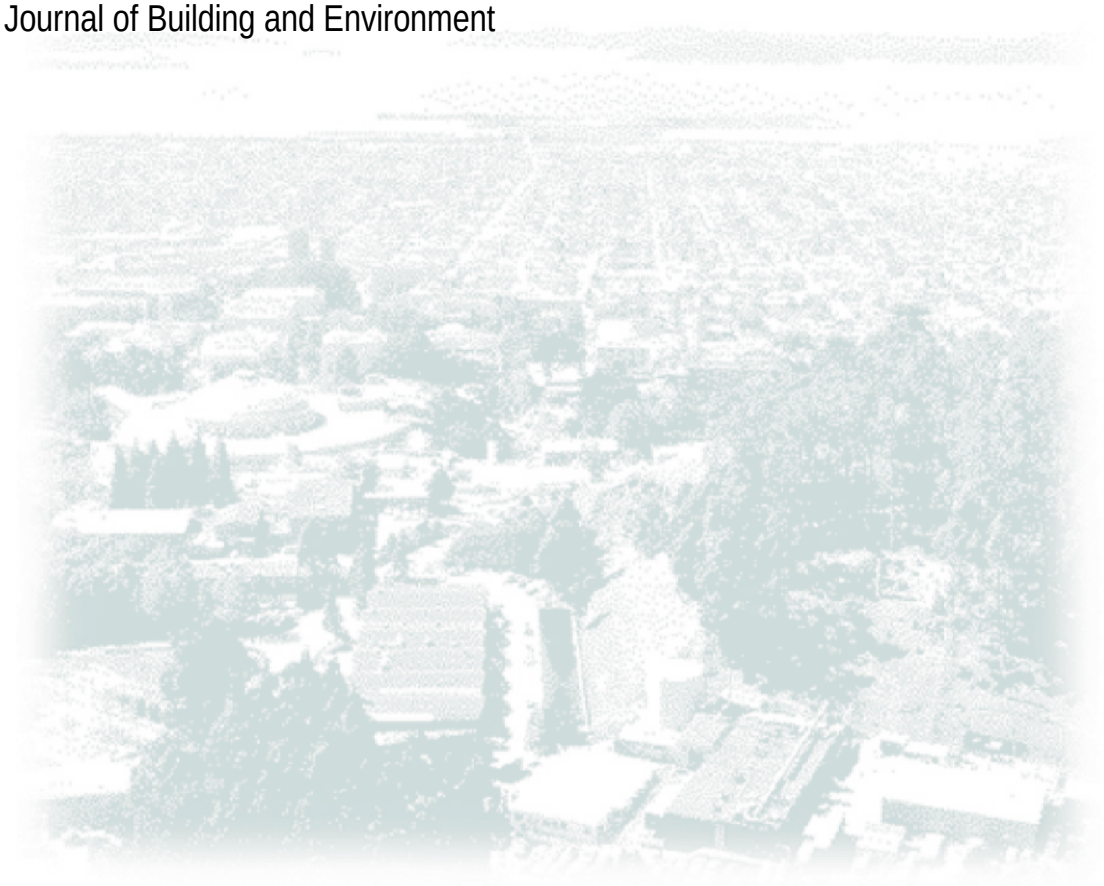

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A Framework for Simulation-Based Real-Time Whole Building Performance Assessment

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Abstract

Most commercial buildings do not perform as well in practice as intended by the design and their performances often deteriorate over time. Reasons include faulty construction, malfunctioning equipment, incorrectly configured control systems and inappropriate operating procedures. One approach to addressing this problems is to compare the predictions of an energy simulation model of the building to the measured performance and analyze significant differences to infer the presence and location of faults. This paper presents a framework that allows a comparison of building actual performance and expected performance in real time. The realization of the framework utilized the EnergyPlus, the Building Controls Virtual Test Bed (BCVTB) and the Energy Management and Control System (EMCS) was developed. An EnergyPlus model that represents expected performance of a building runs in real time and reports the predicted building performance at each time step. The BCVTB is used as the software platform to acquire relevant inputs from the EMCS through a BACnet interface and send them to the EnergyPlus and to a database for archiving. A proof-of-concept demonstration is also presented.

Keywords

EnergyPlus, Energy modeling, Real-time, Building simulation, Building performance, Building controls virtual test bed

1 Introduction

The use of simulation to assess the actual performance of buildings has been addressed by a number of researchers [1,2,3]. The application of model-based performance assessment at the whole building level had been explored by Haves et al. [3]. In their work, the information requirements for a simulation to predict the actual performance of a particular building were addressed and the possibilities for using control system communication protocols to link real-time simulation and the EMCS were discussed.

Clarke et al. [4] demonstrated a prototype control system to integrate simulation using ESP-r within real-time EMCS operation to enhance control capabilities. However, due to the practical interface issues, LabVIEW was used in the test instead of an actual EMCS.

Lee et al. [5] examined the use of the ASHRAE simplified energy analysis procedure (SEAP) in identifying significant deviations from expected building energy consumption and fault detection at the whole building level. Though the on-line version of this technique was discussed, the real-time application was not yet implemented at the time the paper was published. The authors concluded that the SEAP is not a complete representation of any building, and a better simulation model is needed to clearly and accurately define an error threshold to differentiate a true system fault from normal deviation.

Xu et al. [6] developed a prototype hardware-in-the-loop simulation environment for controls testing and training using SPARK (Simulation Problem Analysis and Research Kernel). The mechanism that coupled the real-time SPARK simulation with a real building control system using a hardware interface was described. A variant of the hardware-in-the-loop environment that used EnergyPlus instead of SPARK to test the implementation of the controls of the naturally ventilated part of the new San Francisco Federal Office Building was also reported. The hardware interface provided a generic way to link the simulation with control systems from different vendors. However, this mechanism is not scalable due to the limited capability to exchange data through the analog/digital converter.

In summary, the value of adapting real-time simulation to enhance building performance has been well recognized in the literature. However, a scalable application of this idea has not yet been reported. This paper introduces a framework for linking the actual performance of a building to the simulated performance that represents the design intent or other benchmarks in real time. By real-time simulation, as opposed to off-line simulation, we mean a building model whose simulation time is synchronized with real-time as represented by the computer clock. The realization of this framework using the EnergyPlus, the Building Controls Virtual Test Bed (BCVTB) and the building Energy Management and Control System (EMCS) was developed.

EnergyPlus is a detailed whole building energy simulation program that calculates the building heating and cooling loads, and disaggregates energy end use as well as many other simulation details that are necessary to verify that the simulation is performing as the actual building [7]. Recent enhancements to the program allow the use of time-steps as small as one minute and also allow control strategies to be specified by 'line-code' control programs that are interpreted at run time, providing the flexibility to use programmable supervisory control strategies. Conventionally, EnergyPlus is used for off-line building energy simulation using Typical Meteorological Year 3 (TMY3) weather data, and then the model reports the outputs at the end of simulation.

Haves et al. [8] developed a software called Building Controls Virtual Test Bed (BCVTB) that linked EnergyPlus with control systems. In Wetter et al. [9], a complete redesign has been presented that forms the basis of the here used program. The new design allows expert users to couple different simulation programs for co-simulation [10]. A BACnet interface for the BCVTB has been recently developed. It allows simulation program to communicate with BACnet-compatible building control systems [11].

With the wide deployment of the EMCS in buildings, the dissemination of open protocols such as BACnet has made sensor and control signal information from various components and subsystems in a building more accessible [12]. This makes it possible to use measured data as inputs to the building model in real time.

2 Framework and the Realization

The framework is illustrated in Figure 1. The middleware allows synchronizing simulation time and real time, exchanging data between the real building and the building model, and archiving the time series data of the building actual performance and the simulated performance. The various aspects of the building are obtained through a number of measurements. The building reference model represents the design intent or a benchmark, such as ASHRAE 90.1, and is constructed using a building energy simulation software. Fault

Detection and Diagnosis (FDD) techniques and user interface may be built on top of this framework.

The realization of the framework is shown in Figure 2. The EMCS serves as the data acquisition system to collect the building and environment measurements. The BCVTB serves as the middleware that integrates the EnergyPlus simulation, database and the EMCS, and synchronizes the simulation time with real time. EnergyPlus is employed as the whole building energy simulation tool. The whole system can reside in either the same computer or two different computers connected using a Local Area Network (LAN).

2.1 BCVTB to Implement and Synchronize the Data Flow

The BCVTB is a free open-source software platform for coupling different simulation tools for co-simulation and data exchange with building automation system or databases. It allows expert users of simulation to expand the capability of individual program by linking them to other programs or applications [10]. The BCVTB is an extension of Ptolemy II, a software environment for heterogeneous modeling and simulation [13]. Ptolemy II is a free open-source software developed at the University of California, Berkeley. The BCVTB has two BACnet modules that allow reading from and writing to BACnet devices. The computation capability of Ptolemy II provides data pre- and post-processing needs such as averaging and filtering. The External Interface module in EnergyPlus 6.0 offers data exchange between EnergyPlus and the BCVTB. Ptolemy II provides the synchronization of simulation time to real-time.

2.2 Instrumentation and Data Acquisition

EnergyPlus takes as input a description of the building (geometry, location, materials, window type etc.), its internal loads and HVAC system description. The weather data is specified separately from the input data file when the simulation is launched. All these input data can be categorized into two types: parameters and variables. The parameters refer to those data independent of time and remain constant during the simulation, e.g. building geometry, material, HVAC equipment nominal capacity etc., while variables refer to those data that might change during the simulation, e.g. weather conditions, control setpoints etc. For the real-time application, the variables need to be updated at each time step. Depending on the applications and availability, some of the variables can either be specified directly inside the EnergyPlus input file or be obtained from an external data source, such as HVAC equipment operational schedules and control setpoints with reset, while some of the variables can only be obtained from external data source at each time step, such as weather conditions. The most relevant weather inputs for building performance simulation are outdoor dry bulb temperature, outdoor relative humidity, solar radiation and wind speed and direction. The required measurement accuracies of these weather inputs may vary depending on the building characteristics and the HVAC system in use. For example, modeling a building using natural ventilation requires more accurate wind speed and direction measurement than modeling a warehouse. Therefore, a sensitivity analysis of individual weather variable is necessary to identify those to which the model outputs are particularly sensitive and those to which they are insensitive. It is hence possible to recognize the weather variables which must be chosen with care so that the accuracy of the model output is not compromised.

In order to utilize the real-time simulation predictions, the measurements on building total electric power and fuel consumption, such as natural gas, are the minimum requirement.

Some levels of electric submetering are highly recommended, i.e. the separate electric power measurements for lighting, plug-load equipment and HVAC system.

2.3 EMCS Integration

Most modern buildings are equipped with an EMCS, and thus a wide range of the dynamic inputs are obtainable. Measurements, such as wind speed and direction, and solar irradiation are not typically available in EMCS. If that is the case then supplementary instrumentation will be required. This ensures that all the dynamic input variables for the EnergyPlus model are available. In order to make these data accessible outside the EMCS, an open communication protocol is needed. BACnet is used in this study due to its wide availability. In the case where the EMCS uses a proprietary protocol, a BACnet gateway, typically available from most EMCS manufacturers, is required. Alternatively, the analog or digital interface that is provided with the BCVTB could be used if BACnet is not supported by the EMCS. The BCVTB contains two actors that can read from and write to BACnet devices [11]. The read function makes the building metrics available for the model inputs while the write function may be used to write to supervisory control setpoints. Both actors use a configuration file to specify the BACnet devices, object types and property identifiers. The detailed procedures to create these configuration files and to use these two actors are described by Wetter [10].

2.4 EnergyPlus Integration

Figure 3 shows the architecture of the connection between EnergyPlus and the BCVTB. The simulator actor within the BCVTB links to the external interface in EnergyPlus. In the external interface, the input/output signals that are exchanged between the BCVTB and EnergyPlus are mapped to EnergyPlus objects [10].

The external interface takes three types of inputs from the BCVTB. The three EnergyPlus objects are the ExternalInterface:Schedule, ExternalInterface:Actuator and ExternalInterface:Variable. When the BCVTB passes a value to the ExternalInterface:Schedule object, it will create a new schedule. The other two objects are used the same way as Energy Management System (EMS) actuators and EMS variables, except that their numerical value is obtained from the BCVTB at the beginning of each zone time step. The EMS is a feature of EnergyPlus to provide high-level, supervisory control to override EnergyPlus data [14]. An EMS is able to read a wide variety of EnergyPlus internal variables and use this data to direct various types of control actions [15]. The actuator objects actuate features inside EnergyPlus by overwriting various input parameters, such as weather data, setpoints and equipment specification. Selected EnergyPlus output data can be sent to the BCVTB by using Output:Variable or EnergyManagementSystem:OutputVariable at each zone time step.

2.5 Database Integration

Any database software can be used for data archiving. PostgreSQL was chosen as the database program in this study. A Java-based API was built for applications to communicate with the database. Alternatively, a database actor that is part of the BCVTB could have been used. In Figure 6 and Figure 7, at the extreme right hand end, there are PtolemyII actors named “database” and “database2”, respectively. Both of these are PtolemyII System Command actors and execute a wrapper tool around the database API, in order to send data to the database. At the extreme left hand end of Figure 4, there is an actor called “SQL Statement” which is used to query data from the database.

3 Proof-of-Concept Demonstration

3.1 Facility Information

The facility is a two-storied building located in the Chicago, IL, area built in 2007. The gross floor area of this building is approximately 70,000 ft^2 (6,503 m^2). About 80% of the floor area serves as a gymnasium-like drill deck for personnel training and ceremonies. The rest of the building is used for office and classroom, and is lightly occupied. A distributed Direct Digital Control (DDC) control system is installed in this building.

There are two 100-ton (352 kW) air-cooled chillers and associated chilled water pumps providing cooling for the whole building. The chilled water hydronic system is designed as primary-secondary system with constant speed primary pumps and variable speed secondary pumps. The chilled water system is enabled based on schedule and outside air temperature. During the cooling season (From April to October), if there is a call for cooling and the outside air temperature is above 55°F (12.8°C), the chilled water system is enabled. The chillers loads/unloads the compressors to maintain the leaving chilled water temperature at 44°F (6.7°C). The two secondary pumps are modulated in sequence to maintain a differential pressure of 10 psi (68.9 kPa) as sensed near the end of the secondary piping run.

Heating is supplied by the campus-wide steam system through a steam-to-water heat exchanger. The hot water hydronic system is designed as primary-only variable water flow system with two hot water pumps. The heating system is enabled when outside air temperature is below 68°F (20°C).The hot water supply temperature set point is maintained by modulating the steam valve. The set point is reset based on outside air temperature. When outside air temperature is 0°F (-17.8°C), the set point is 180°F (82.2°C) and when outside air temperature is 65°F (18.3°C), the set point is 120°F (48.9°C). The two hot water pumps are modulated in sequence to maintain a differential pressure of 10 psi (68.9 kPa) as sensed near the end of the hot water piping run.

The drill deck is served by two identical single-zone Variable Air Volume (VAV) Air Handling Units (AHU). During the normal operation, one of the two AHUs serves the entire drill deck. They alternate to equalize runtime on a weekly basis. At some special events with high cooling demand, e.g. a graduate ceremony, a manual timer switch can start the second AHU. The fan speed and the discharge air temperature are modulated in response to the heating or cooling demand in the drill deck. The heating coil valve, cooling coil valve and mixed air dampers modulate in sequence to maintain the discharge air temperature set point. The return air fan is modulated to maintain an air flow difference between the supply air flow and the return air flow.

The office area is served by one VAV AHU with VAV terminal units.

There is a classroom served by a single-zone VAV AHU. Since the classroom is seldom used, most of the time, this single-zone VAV system remains off.

The drill deck is served by two variable-air volume (VAV) air handling units (AHU) with heating and cooling capability. Unit operation depends on the occupancy of the drill deck space. The office and administrative area is served by one VAV air handling unit with VAV terminal units (with hot water reheat). There is an instantaneous steam-to-domestic hot water generator for domestic hot water service. Building electric and water meters are also read by the DDC

system. Operator workstations provide graphics with real-time status for all DDC input and output connections.

3.2 Instrumentation

One innovative feature of the proposed technique is the introduction of the weather data into the simulation at run time. These weather variables are outdoor air dry bulb and relative humidity, wind speed and direction, direct normal solar radiation and diffuse solar radiation. Since this experiment served as a proof-of-concept, particular attention was given to the instrumentation selection so that the model output uncertainties that arise from the uncertainties of these measurements can be minimized. An initial guess of the most influential weather variables were the outside air dry bulb and relative humidity, followed by the solar radiation, the wind speed and the wind direction. A preliminary instrumentation selection was done accordingly. The selected measurement accuracies are listed in Table 1.

A sensitivity analysis was conducted to identify the weather variables to which the model outputs are particularly sensitive. The Differential Sensitivity Analysis (DSA) method described by Lomas and Eppel [16] was used to carry out the sensitivity analysis. This method varies one weather variable for each simulation while the others remain at their base values. Hence, the change in a predicted parameter is a direct measure of the effect of the change made in the weather variable. Here, the annual building electricity consumption and district heating energy consumption were used as the predicted parameters. Since the weather impacts on the building energy performance are small during unoccupied hours, the predicted parameters only takes into account the energy consumption during occupied hours, i.e. from 6am to 10pm. Repeating the simulations for each weather variable enables the individual effect to be determined by

$$\Delta p_i = p_i - p_b \qquad (1)$$

where p_i is the value of predicted parameters using modified value of input i, and p_b is the value of predicted parameters using base value of inputs. The Typical Meteorological Year 3 (TMY3) data was used as the base value of the weather variables. The change of the weather variable should be selected in such a way that the most likely range of the weather measurement is covered. Assuming the weather measurements are normally distributed, it is appropriate to choose two times of their standard deviation as the changes of each weather variable since there is a 95% probability that the weather variables lie inside this bound. Therefore, the modified weather variable is determined by

$$x = x_{base} \pm 2s \qquad (2)$$

where x_{base} is the base value for each weather variable and s is the standard deviation of each weather measurement. The results of the individual effect were presented as bar charts in Figure 4 and 5. As can be seen, the outside air temperature is the most sensitive variable in both the electricity and the heating energy consumptions and the outside air relative humidity is the second most sensitive variable in the electricity consumption. However, outside air temperature and relative humidity sensors with higher accuracy than the ones specified in Table 1 would increase instrumentation cost. It was decided to select these two sensors based on the accuracies specified in Table 1 augmented with an aspirated radiation shield. The wind speed and wind direction were the least sensitive variables and their sensitivities were two orders of magnitude less than that of the outside air temperature, which indicates that their specifications were not necessary. We decided to choose the wind speed and wind direction sensors with the accuracies

specified in Table 1 since their costs were small compared to other sensors. As shown in Figure 4, less accurate beam and diffuse solar radiation measurements could have been used. However, the accuracies of the two solar radiation measurements specified in Table 1 were obtained from what appeared to be the only off-the-shelf pyranometer that outputs beam and diffuse solar radiation at the time the project started.

Since the building do not behave as a superposable system, the DSA method is not suitable to find out the total sensitivity of the predicted parameters. Lomas and Eppel [16] suggested the Monte Carlo Analysis (MCA) method be used to estimate the total sensitivity. This is a separate topic and subject to future research.

In addition to the weather measurements, electric sub-metering and thermal meters had also been installed for the purposes of model calibration and building performance assessment. The electric sub-metering was able to disaggregate the electricity usage for lighting, plug-load and HVAC. The thermal meters measured the cooling and heating energy usage. These meters were selected according to the specifications from Gillespie et al. [17].

3.2 System Architecture

A whole-building EnergyPlus simulation model representing the design intent of the envelope, the HVAC system, the lighting system and the control system was created. The model was then calibrated based on the information collected from design documents as well as the EMCS trending data from April to July [18]. Since the EMCS uses a proprietary communication protocol, a BACnet server was installed and connected to the EMCS so that the BACnet client included in the BCVTB can communicate with the EMCS. The BCVTB was installed in a separate computer from the one running the EMCS. The real-time simulation was launched by starting the BCVTB through the Graphical User Interface (GUI) or through the console. The latter allows use of the BCVTB in an automated workflow or in a window-less system.

There are two processes running in parallel. The BACnet reader actor acquires the relevant EMCS data through an Ethernet connection. The sampling interval was 5 minutes. The data was then passed to a PostgreSQL database. Figure 6 illustrates the realization of the BACnet read process in the BCVTB.

The BCVTB established the communication with the EnergyPlus simulation program. The EnergyPlus simulation time step was 15 minutes. At each time step, the EnergyPlus simulator receives the weather data, i.e. the outdoor air dry bulb temperature and the relative humidity, the wind speed and direction, and the solar irradiations, as inputs and advances the model by one time step. Since the BACnet reader was configured to use a 5 minute time step, while EnergyPlus used a 15 minute time step, the inputs to the EnergyPlus simulation were averaged over the 15 minute interval. Once the simulation is finished for that time step, the BCVTB writes the results to the database. The time steps and the run period have to be specified before starting the simulation. Figure 7 shows the block diagram that reads data from the database, sends them to EnergyPlus, and writes data to the database. Since the EnergyPlus data input file can only specify the begin day and month, unless the simulation starts right at mid-night, a delay-start of the simulation is needed in order to ensure the synchronization between the EnergyPlus simulation time and the wall clock time. In the BCVTB GUI, synchronization of the simulation time and real-time can be achieved by checking a check box as shown in Figure 8.

3.3 Results & Discussions

The first test was to validate the real-time data acquisition process. The existing EMCS has about 1,200 control points including both physical points and virtual points such as control set points. About 700 control points that are relevant to the demonstration have been made accessible through the BACnet server. The BACnet reader in the BCVTB reads these data points and sends them to the database. Several manual checks have been conducted by exporting the data from the database to a spreadsheet and comparing to the trending data in the EMCS over a one-month period. The comparison shows that the data stored in the database match exactly the trending data in the EMCS.

Two checks had been done to validate the real-time EnergyPlus simulation. The first check was to compare the simulation results of the real-time simulation with that of the off-line simulation using EnergyPlus weather file, i.e. TMY3 weather data. One comparison of the simulation results, the building total electric power, is shown in Figure 9. The deviations in the simulation results were due to the differences between the actual weather data and the TMY3 weather data, which indicated that the real-time simulation successfully overwrites the selected weather parameters in the weather file and takes the real-time weather measurements as its inputs. The comparisons between the actual weather data and the TMY3 weather data for the outdoor air dry bulb temperature, the direct normal solar irradiation and the diffuse solar irradiation are shown in Figure 10, 11 and 12 respectively.

In the second check, a customized EnergyPlus weather file was created using the actual weather data stored in the database. The real-time EnergyPlus simulation results stored in the database were then compared to that of the off-line EnergyPlus simulation using the customized weather file. As can be seen from Figure 13, the simulation results of the building total electric power agree to each other, which further validates a working real-time EnergyPlus simulation using the instantaneous measured weather data.

One direct application of the real-time EnergyPlus simulation is the whole building performance assessment. Figure 14 compares the real-time simulated building total electric power with the actual measurement. Significant differences between the simulated and measured performance are highlighted in Figure 14. The highlighted areas enclosed by the oval dash lines represent the differences occurred during occupied hours while that enclosed by the rectangle dash lines represent the differences occurred during unoccupied hours. Further breakdown of the electric power indicated that the different chiller operation strategies were the cause of the considerable performance deviations during occupied hours, as shown in Figure 15; and the lights left on overnight was the cause of the deviations during unoccupied hours, as shown in Figure 16. The abnormal operations like the lights on during night were readily identified. However, the causes of the anomalies like the cooling electric power differences are more difficult to discover. To aid the diagnostics, root-cause analysis techniques, such as the techniques studied by IEA Annex 25 [19], can be incorporated into this tool to expand its capability in FDD.

4 Conclusions and Future Work

A framework that allows the comparison between the building actual performance and the desired performance is proposed. The realization of this framework using EnergyPlus, the BCVTB and the EMCS has been successfully developed and tested in a real building. The proof-

of-concept demonstration also shows the prospect of this application in supporting the building operation and maintenance.

The future work is identified as following:

1. EnergyPlus models all HVAC systems in steady states. To identify the control faults, such as faulty implementation of supervisory or local control sequences and the system instability, a simulation tool that can model the system dynamics, such as Modelica [20], should be used to supplement EnergyPlus.
2. To handle the leap year and to start the real-time simulation at any given time need to be addressed in the EnergyPlus run control.
3. EnergyPlus employs "warm up" days to ensure a proper building initial condition to start the simulation. Therefore, one full day of measurements of the actual weather conditions is needed to replace the corresponding entries in the weather file for the "warm up". Now, this process is done manually every time the system starts. It is necessary to automate this process.
4. Incorporate FDD techniques into this tool and develop a good user interface.

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Table 1 Weather measurement accuracy

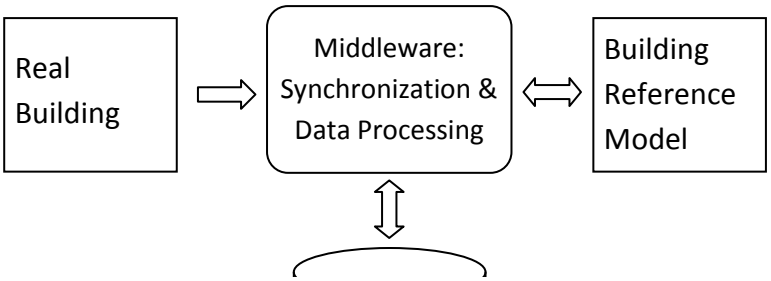

Figure 1 Illustration of the framework

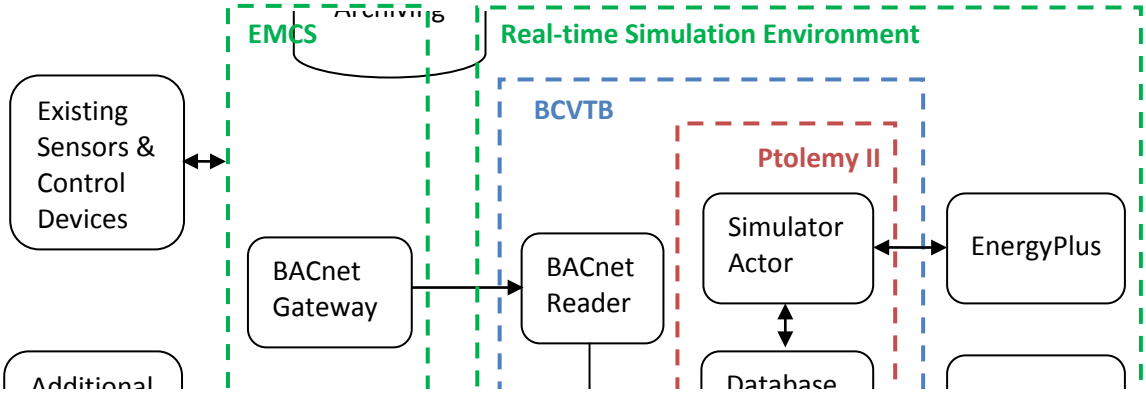

Figure 2 Realization of the framework

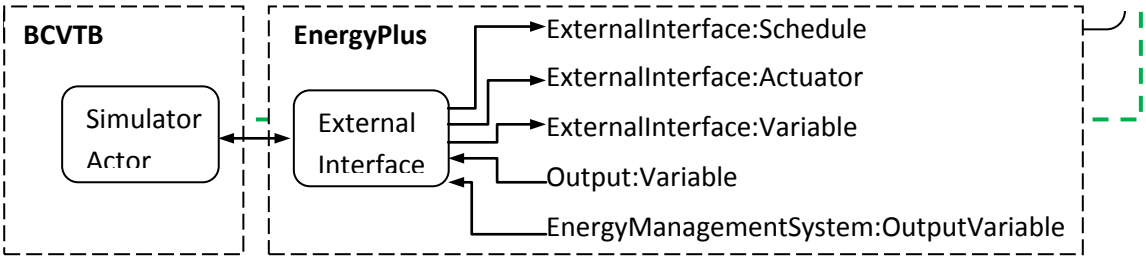

Figure 3 Architecture of BCVTB and EnergyPlus connection

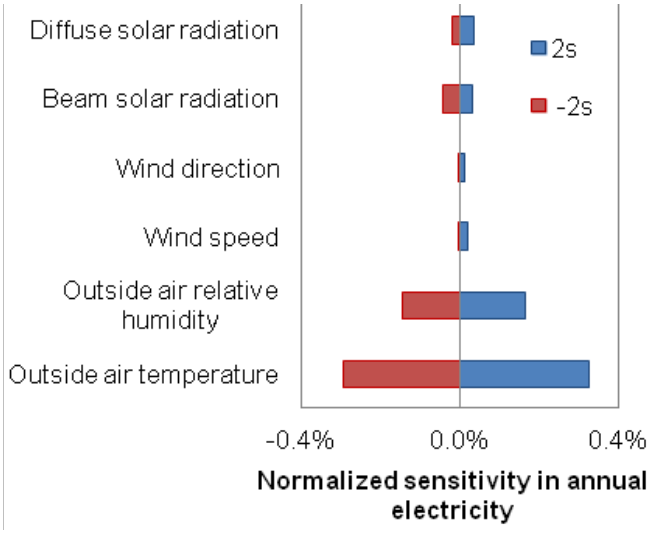

Figure 4 Sensitivity analysis results for annual electricity usage

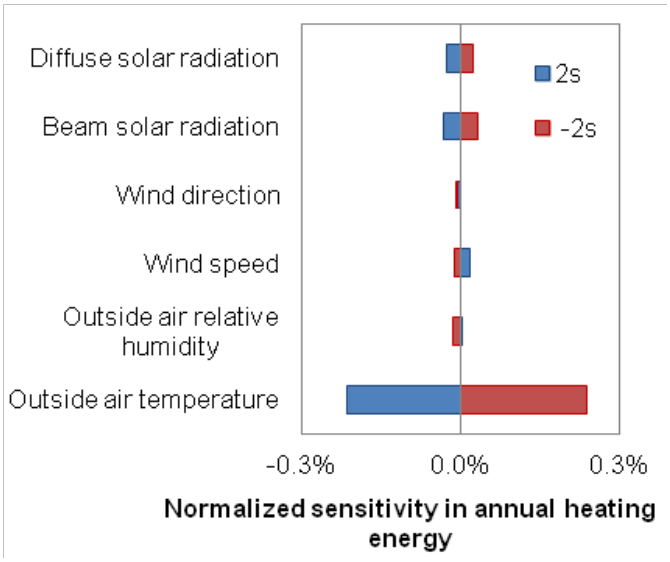

Figure 5 Sensitivity analysis results for annual heating energy consumption

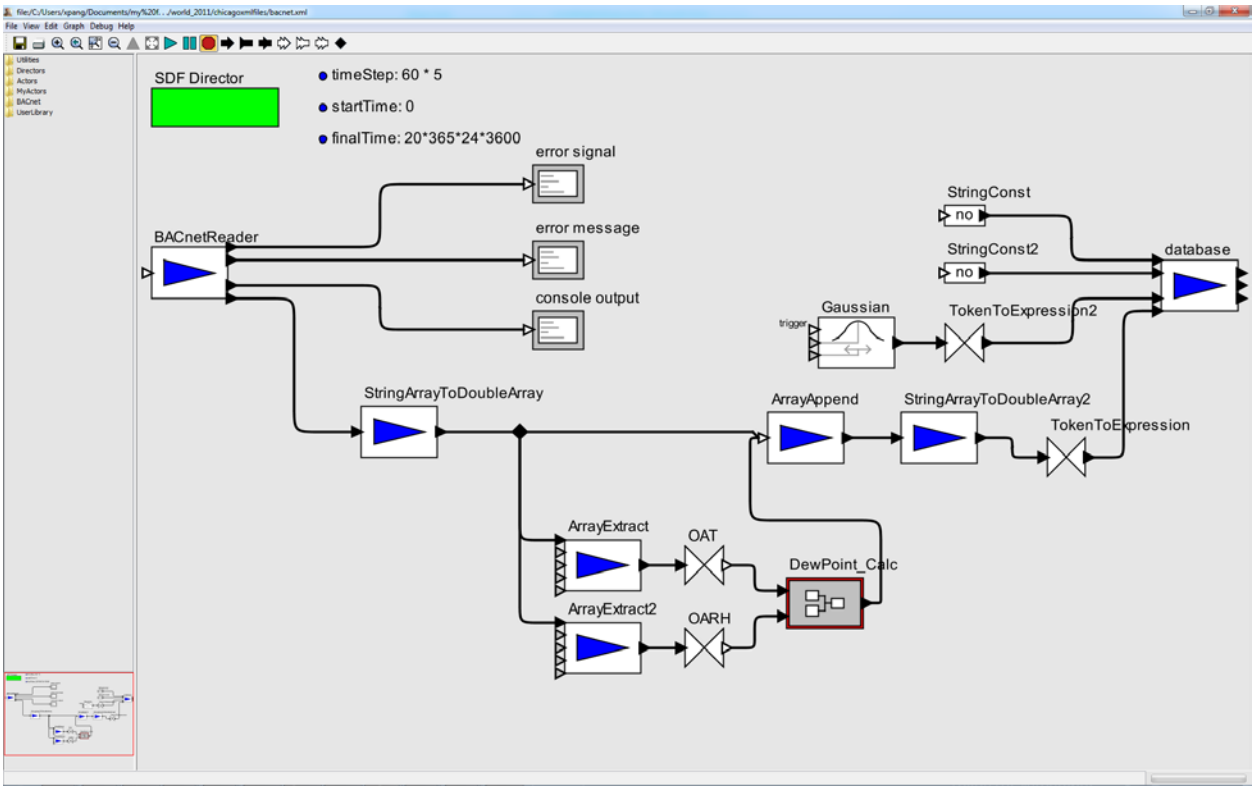

Figure 6 Graphical programming of the BACnet read process in the BCVTB

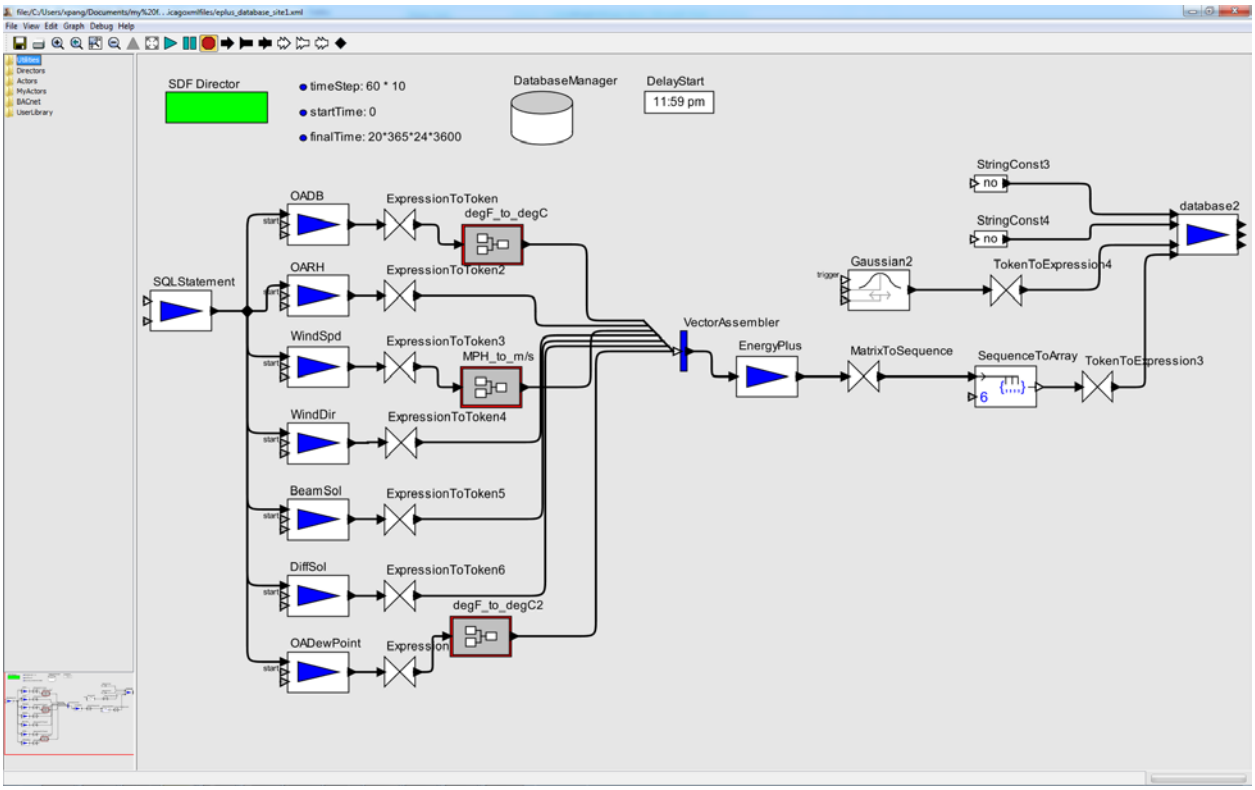

Figure 7 Graphical programming of EnergyPlus simulation in the BCVTB

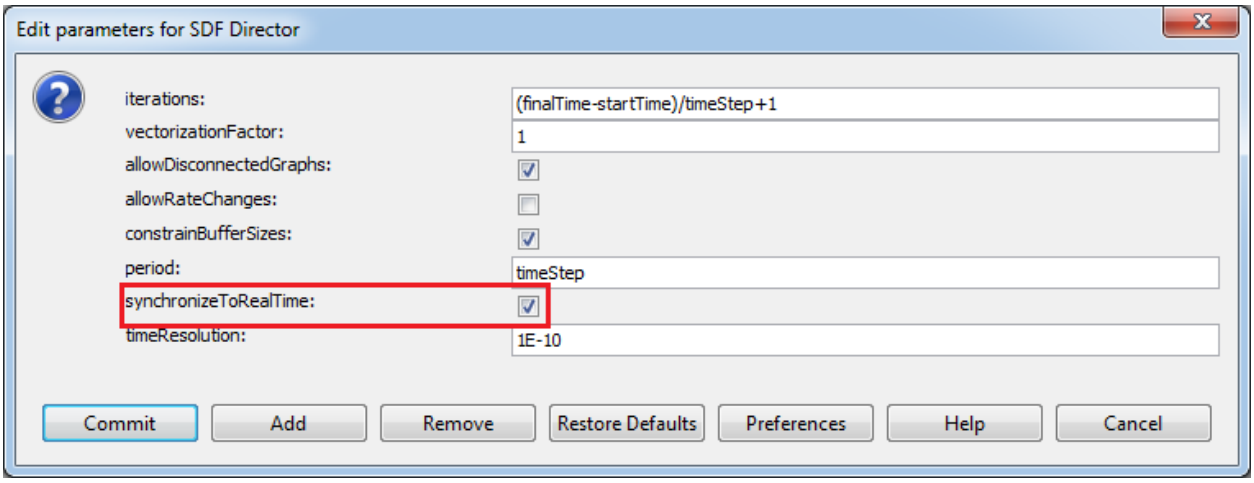

Figure 8 Synchronization of simulation time to real time

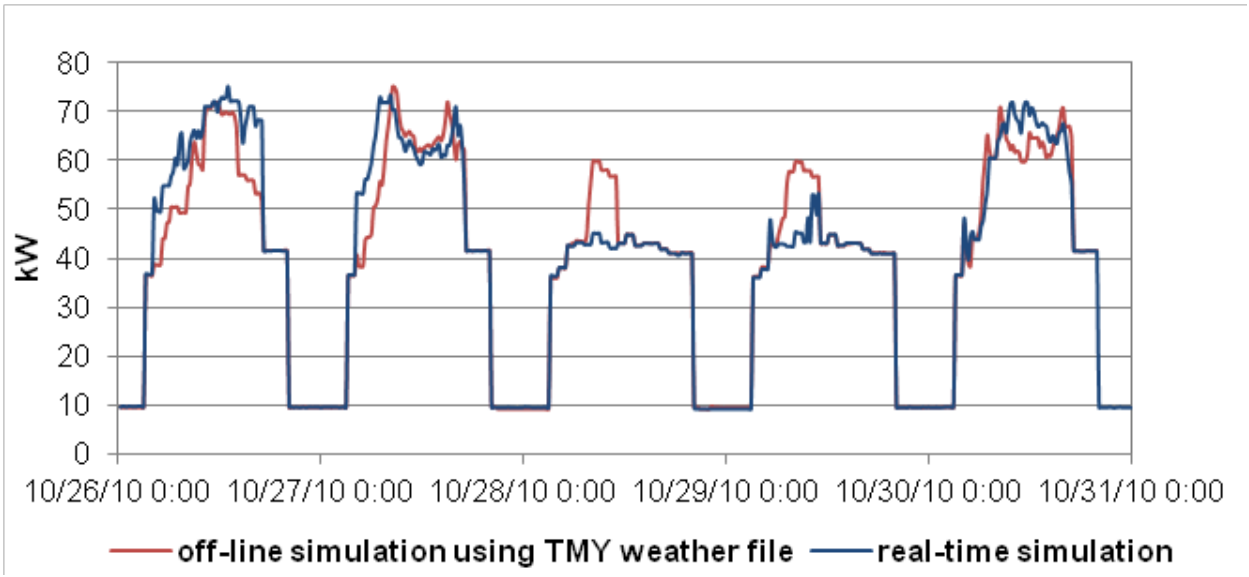

Figure 9 Total electric power comparison between real-time simulation and off-line simulation using TMY3 data

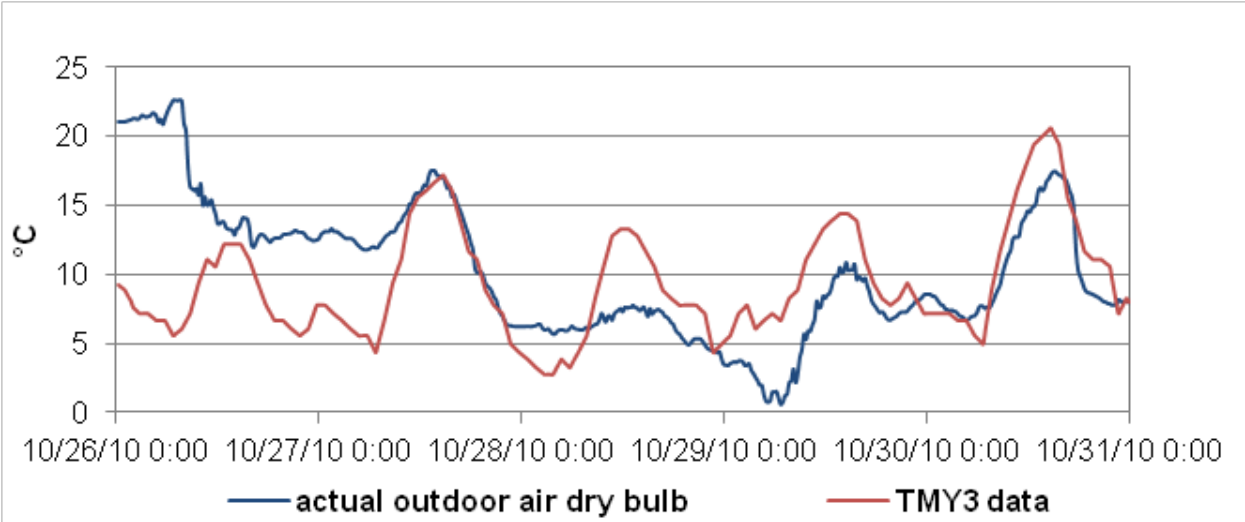

Figure 10 Outdoor air dry bulb temperature comparison between the actual measurement and the TMY3 data

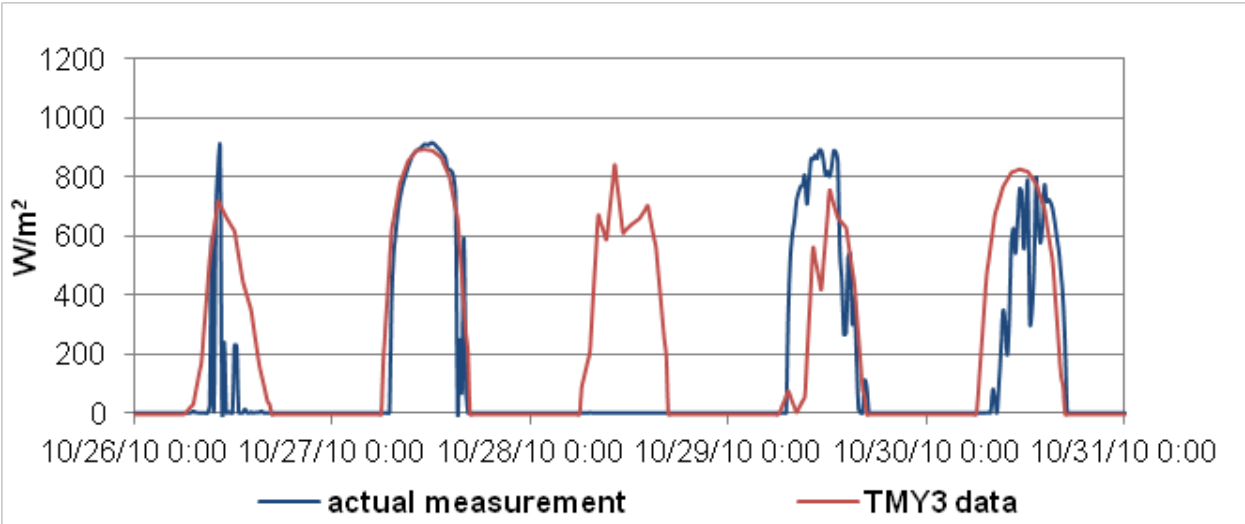

Figure 11 Direct normal solar irradiation comparison between the actual measurement and the TMY3 data

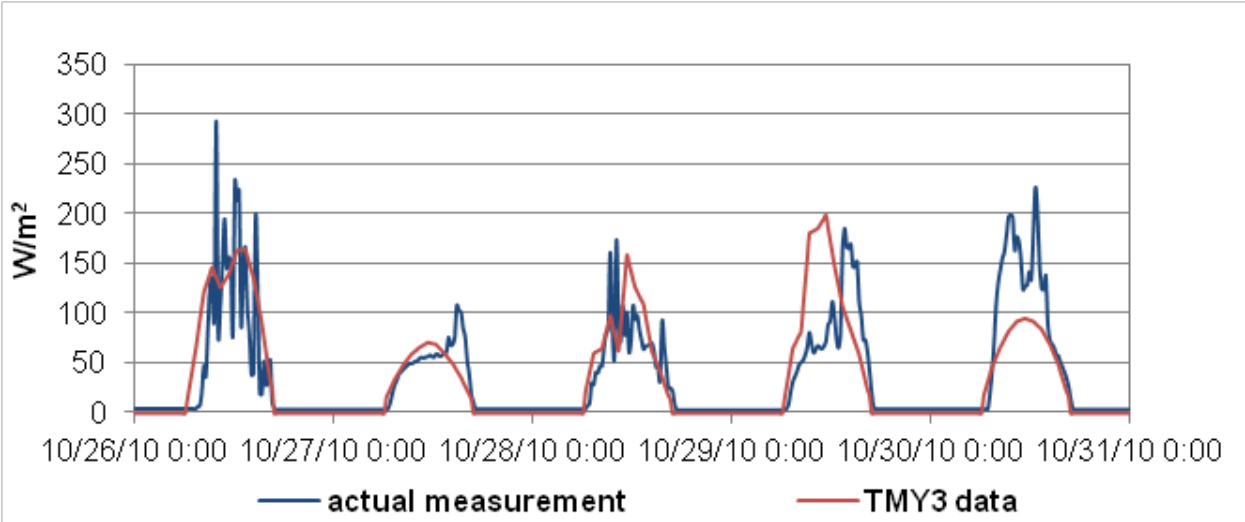

Figure 12 Diffuse solar irradiation comparison between the actual measurement and the TMY3 data

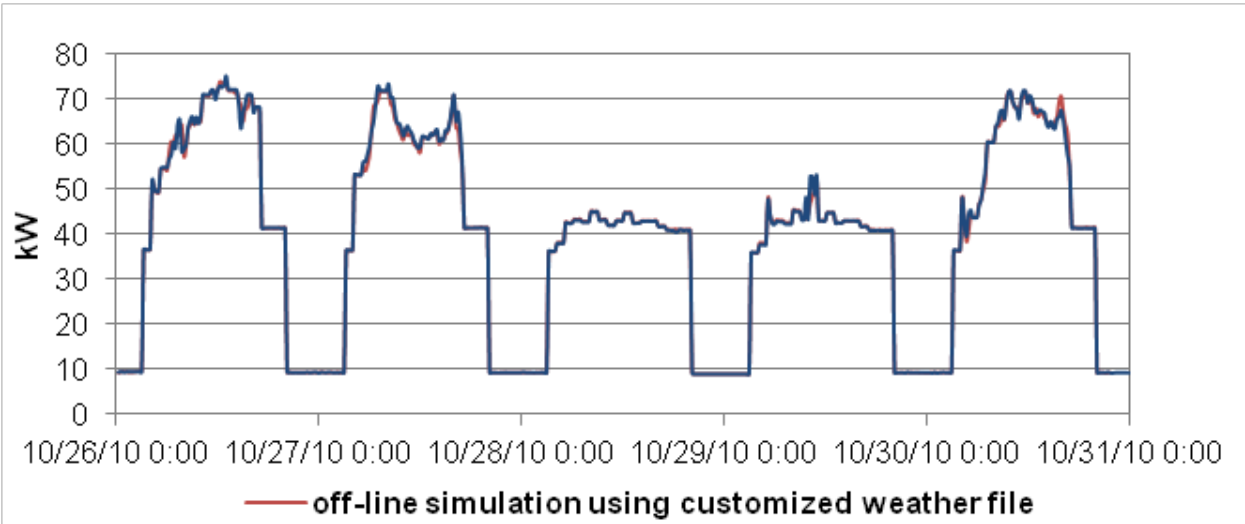

Figure 13 Total electric power comparison between real-time simulation and off-line simulation using the customized weather file

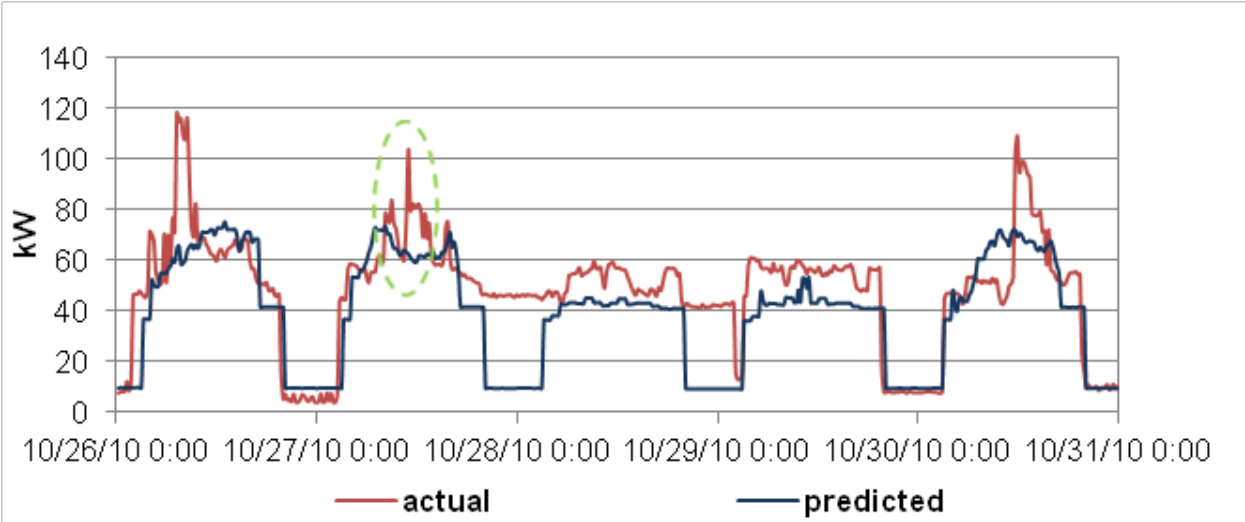

Figure 14 Total electric power comparison between real-time simulation and actual measurement

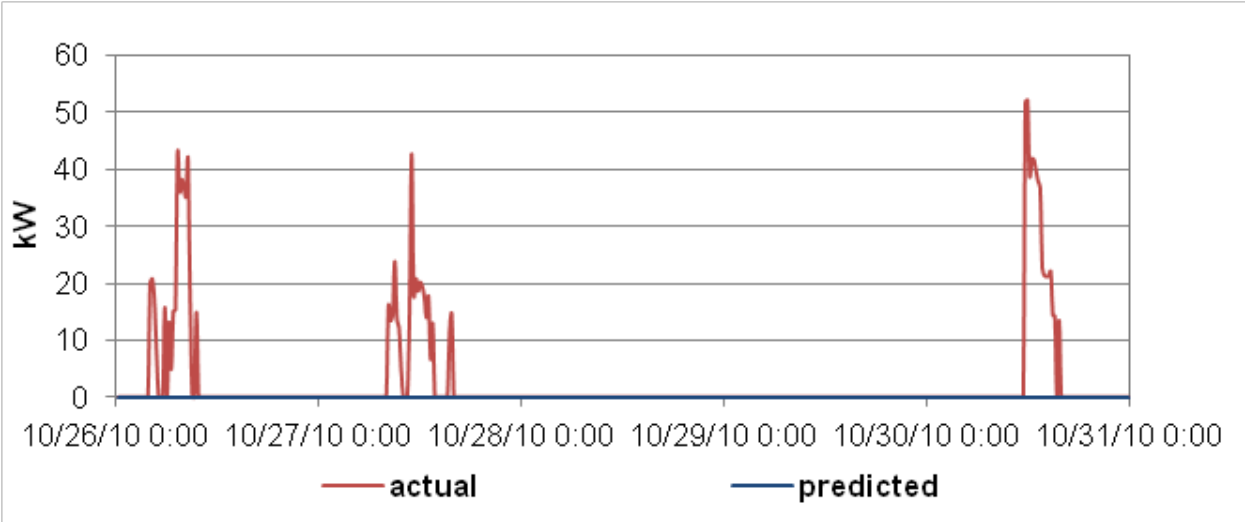

Figure 15 Cooling electric power comparison between real-time simulation and actual measurement

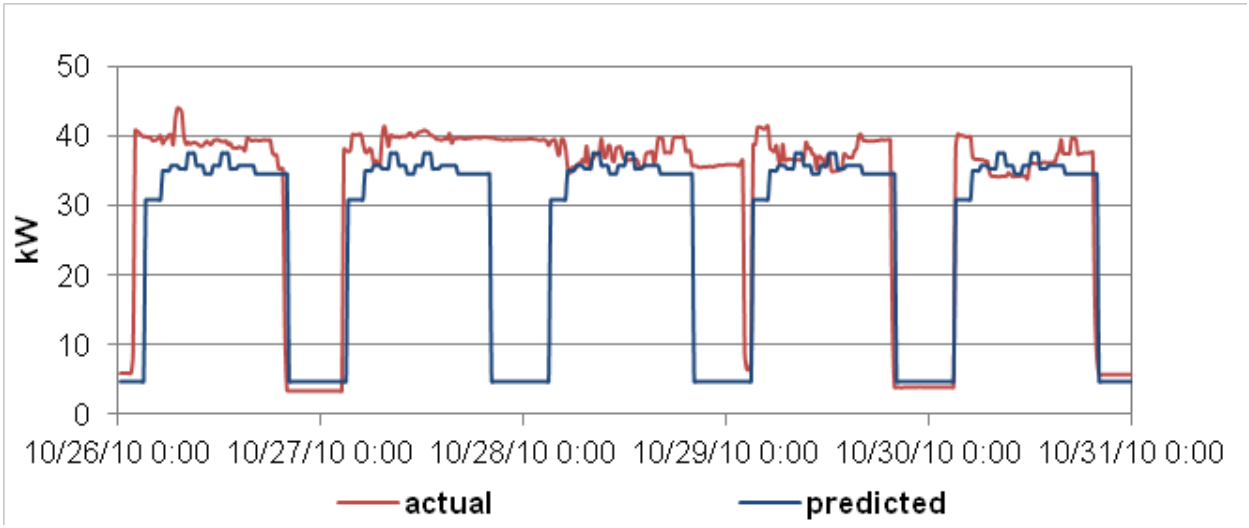

Figure 16 Lighting electric power comparison between real-time simulation and actual measurement

Table 1 Weather measurement accuracy

Weather Variable	Measurement Accuracy
Outdoor air dry bulb	0.1K
Outdoor air relative humidity	(1.0+0.008×reading)% RH
Wind speed	0.09 m/s
Wind direction	5 degrees
Direct normal solar radiation	2% of reading
Diffuse solar radiation	2% of reading