AN INTEGRATED INFRASTRUCTURE FOR REAL-TIME BUILDING ENERGY MODELING AND FAULT DETECTION AND DIAGNOSTICS

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ABSTRACT

It is common that a building consumes 20% more than its design intent. The inconsistency between design and operation is a driving force. To address this issue, we present an integrated infrastructure for real-time building energy modeling, visualization and energy Fault Detection and Diagnostics (FDD). A building information model (BIM) based database is developed for the purpose of storing building operational, simulation and FDD analysis data. A BIM to building energy modeling (BEM) middleware is developed to automatically generate energy modeling codes. A connector is developed in Building Control Virtual Testbed (BCVTB) which enables the storage of building energy management system (BEMS) data into a BIM based database in real-time fashion. Finally, this infrastructure is implemented in a real-building and continuously performs its data collection and visualization functions.

INTRODUCTION

The World Business Council for Sustainable Development recently published their first report on energy efficiency in buildings stating that buildings are responsible for at least 40% of energy use in many countries (Lafarge and UTC, 2008). To achieve the goal of energy efficient buildings, there have been numerous studies showing that offline building energy modeling can help architects and engineers make decisions to save energy while maintaining indoor thermal comfort (Thornton, et al., 2011). However, during real-time building operation, some required design information may be lost or may change for detailed building energy modeling and FDD. In addition, building system operational information may be wrapped in a proprietary interface and not available to facility managers, researchers, etc. During past decades, there have been several pioneering research projects addressed the issues above. Building information modeling has been developed by several design software vendors such as Autodesk and Bentley to provide data interoperability among different design tools (AutoDesk, 2011). Open communication protocols such as BACnet (A Data Communication Protocol for Building Automation and Control Networks, ASHRAE, 2008) make building operational data more accessible. Typically, control vendors provide a tool that can read and store sensor information from the BEMS system. This kind of tool, however, does not provide users flexibility because the room allowed to interact with the BEMS system online is limited. For example, if a user has an EnergyPlus model, and wants to calibrate model based on real time sensor information, the model can be used as part of the model predictive control system. One of the preconditions to work out is to have an independent network communication system that does not rely on the vendor specific communication system. A BACnet communication system sitting in Building Control Virtual Test Bed (BCVTB) has been developed in Lawrence Berkeley National Lab (LBNL), which is based on BACnet Stack (An open source BACnet protocol stack for embedded systems) (Thierry, et al., 2011).

Currently, the main technology barriers/challenges preventing smoothing transitions from offline to online building modeling and FDD can be summarized:

1. *Lack of data integration from the design stage to the operation stage*. A desirable building life cycle delivery process should include design, construction, commissioning and post-occupancy evaluation. It involves tremendous information storage and exchange. Although there were BIM based design tools such as Revit (Autodesk, 2011), and tools like BCVTB (Wetter, 2011) to solve software interoperability issues during modeling stage, the data integration from the design stage to the operation stage is still missing. This results in a time consuming and error prone real-time building energy modeling stage, and also impacts the results of model-based FDD (Lee, et al., 2007, O'Neill et al., 2011).

2. *Lack of a scalable and structured database for the purpose of real-time implementation*. Current state-of-

art BEMS can collect a rich set of data from different building systems and equipments (HVAC, lighting, etc.) in the magnitude of minutes. How to store those data into a structured database so that the database performance will not be degraded with growing data is a critical and practical issue for real-time implementation. In addition, a scalable database which can be applied to different buildings (e.g. size and type) with different systems is still missing.

To address those two issues, in this paper, we present an integrated infrastructure for real-time building energy modeling and energy FDD. The core of this infrastructure includes a BIM-based database, real-time data acquisition system, and BIM to BEM (building energy modeling) toolkit. We extend BCVTB through a new BCACnet-Database transition actor which enables users to store the raw operational data to a BIM-based database. We also applied this infrastructure into a real building application which has a real-time building model including building envelope, HVAC components, building controls, energy visualization dashboard and FDD.

TECHNOLOGY APPROACH

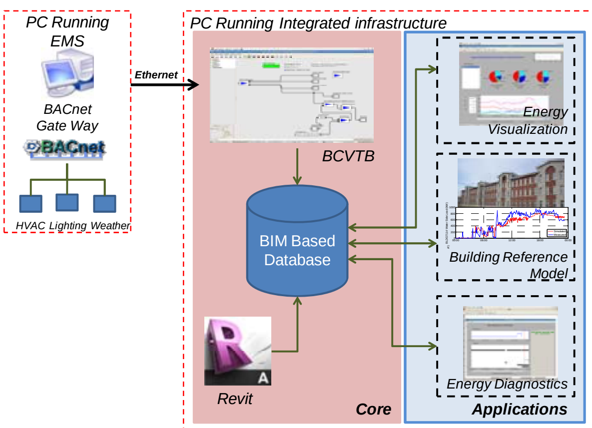

Figure 1. Overview of the Integrated Infrastructure

Figure 1 shows an overview of the proposed integrated infrastructure. This infrastructure integrates different hardware and software components in a holistic manner which provides the capability of real-time simulation, data acquisition, energy visualization and FDD. In addition, through this infrastructure, the users, who are facility managers, can quickly identify abnormal activities for the current building energy systems operation and understand the possible root causes. It has two layers, namely, core layer and application layer.

Core Layer

There are four key elements in the core layer:

1) BIM-based Database

This BIM-based database is a repository for building properties. This includes: a) static information directly from a building Industry Foundation Classes (IFC) file which is generated by a Revit model and b) dynamic information from building operation data. The purpose of this database is to perform information exchange among multiple function modules, which includes a simulation module, a visualization module, a FDD module and a real time data acquisition module. This BIM-based database is a core entity for this integrated infrastructure. The development of this database scheme is composed four elements:

a) Building Static Information

Building static information includes building envelope information related to thermal performance, building occupancy information and building system information. Building system include lighting system, power system such as plug load etc., and HVAC system. Since thermal modeling is the purpose of storing building envelope information, the schema entities follow the traditional building energy modeling naming conventions. The physical elements are categorized at three levels: building, zone (shown in Figure 2) and room (shown in Figure 3). At the building level, location and weather information are stored. At both zone and room levels, wall, window and material property information can be stored.

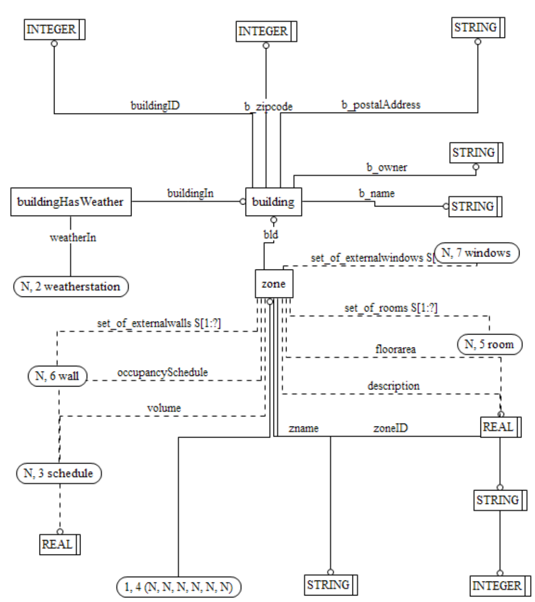

Figure 2. Building and Zone

To conduct a full building energy simulation, property information about the HVAC system and the power system is also necessary. The schema generalizes all equipment with an equipment entity, and differentiates the usage with a function attribute. Then based on where the equipment is located, the system level equipment is categorized into one of three categories: primary system, secondary system and terminal system. Component level equipment is categorized into "component". The equipment entity is shown in Figure 4. Primary system, secondary system, terminal system and equipment are shown in Figures 4 and 5, respectively.

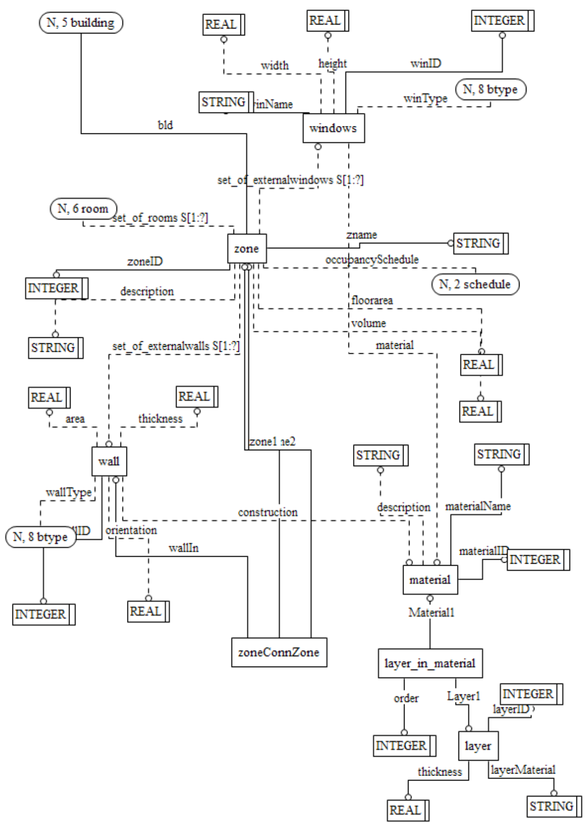

Figure 3. Relationship between zone and room, wall, window and material

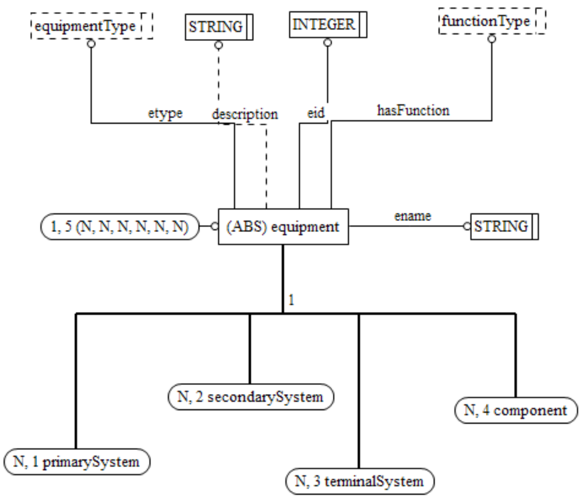

Figure 4. Equipment

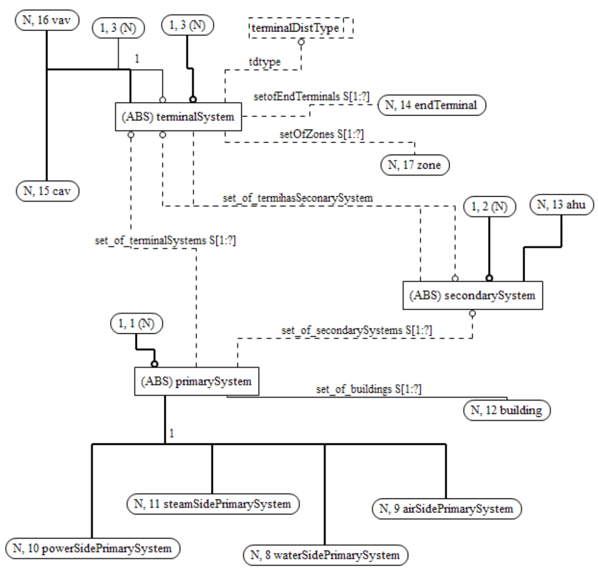

Figure 5 Primary, Secondary and Terminal System

b) Operational Information

The building operational information refers to the information coming from building BEMS system including all sensor data, command signals and control set points. This is also how operational data is categorized. In each category (sensor, set point, and control signal), entities are further separated based on the physical definition (temperature, velocity, volume flow rate, etc.). The sensor schema developed based on this categorization is shown in Figure 6. To store the dynamic value of a sensor, timestamp is used as attribute at the smallest category level. As an example, Figure 7 shows the schema for temperature sensor.

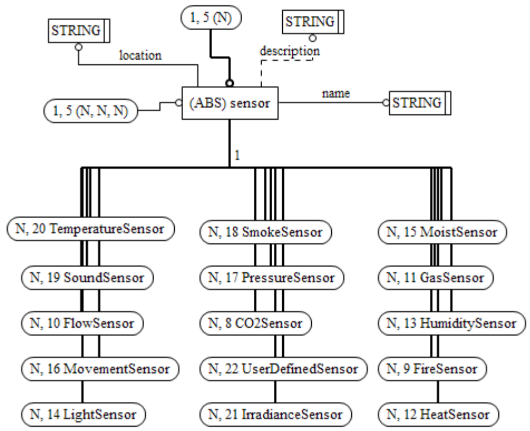

Figure 6 Sensor Schema

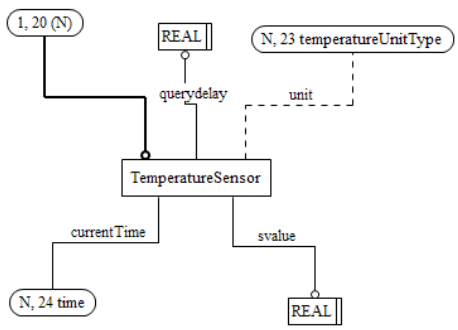

Figure 7 Temperature Sensor Schema

c) Simulation Information

To store the output from real time energy simulation, the following entities are introduced: simulationdata, temperaturesim, flowsim, humiditysim, loadsim, pressuresim, factorsim and efficiencysim. The schema for Simulationdata is shown in Figure 8.

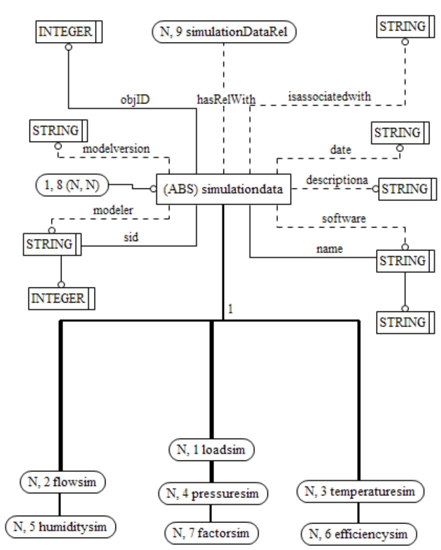

Figure 8 Simulation Data

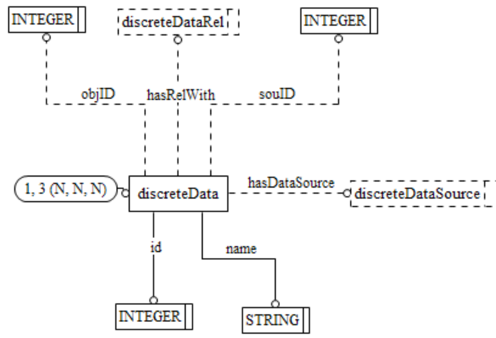

Figure 9 FDD Discrete Data

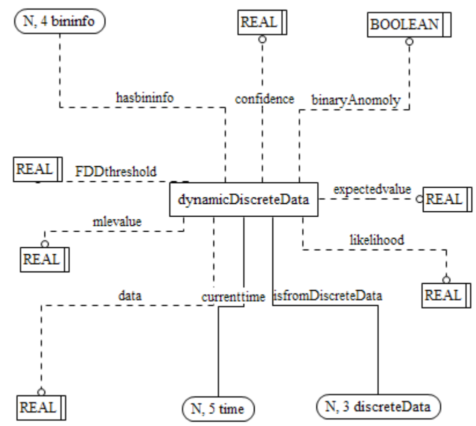

Figure 10 FDD Dynamic Discrete Data

d) FDD Information

A static table that stores the FDD data points and a dynamic table that stores the FDD outputs are the minimal configuration requirements for FDD information. In the current schema, the 'discretedata' entity is used for storing the FDD static information, the 'dynamicDiscreteData' entity is used to store the FDD dynamic information, which are shown in Figures 9 and 10, respectively.

2) Automatic Simulation Code Generation

Once the BIM database is set-up, the static information is collected through Building Information Modeling Test Bed (BIMTB), a middleware which reads building information from a neutral format file (IFC/gbXML), and stores that data in the centralized BIM database. An IFC View Definition, or Model View Definition (MVD), defines a subset of the IFC schema, which is needed to satisfy one or many exchange requirements of the architectural, engineering and construction (AEC) industry. This is also one of the requirements for successful information exchanges. The MVD for architecture and HVAC relevant information is shown in Figures 11 and 12, respectively.

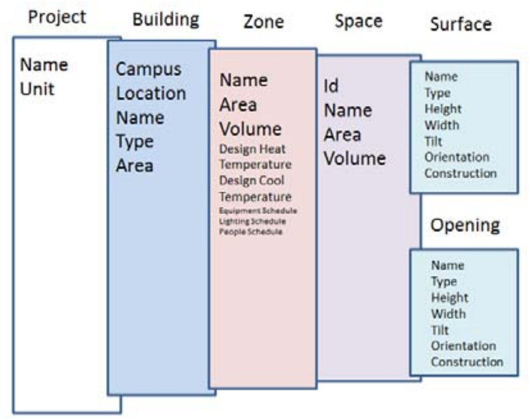

Figure 11 MVD for Architecture

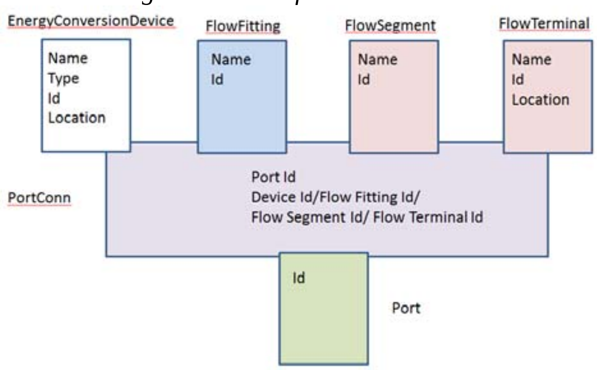

Figure 12 MVD for HVAC Systems

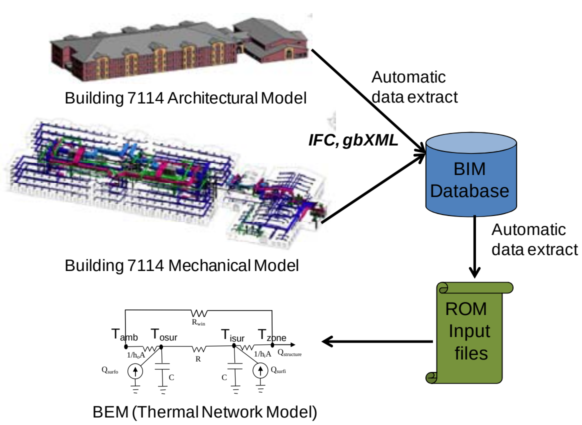

Figure 13 BIM to BEM Flow Chart

Figure 13 shows the flow chart from BIM to Building Energy Modeling (BEM) process. The information from both Revit architecture and mechanical drawings were exported to IFC and gbXML files. The unique difficulties of Autodesk Revit are: (1) Revit does not support the translation of a HVAC zone to a IFC zone;(2) mapping between a zone and an envelope surface does not exist in the IFC file; (3), mapping between a zone and HVAC equipment does not exist in the IFC file; and (4) Native translation of Revit model to the IFC file does not contain the connection between flow terminals and equipment. To address the above problems, the following approaches are proposed:

- Architectural information is read from a gbXML file, which can also be exported given a Revit model
- HVAC information is read from a refined Revit HVAC model through GraphiSoft plugin (Graphisoft, 2011) for Revit MEP 2011.
- The link between the architectural information and HVAC information is established through the geometry attribute, where the coordinates of each flow terminal are mapped to its corresponding zones.

Beside the issues with HVAC zones, the thermal properties for each material layer can be only entered manually as a single thermal resistance value after calculated outside the software. Input files for both building envelope and HVAC models are automatically generated from the data extracted from IFC/gbXML files.

3) Real-time Data Acquisition

There are three main actors in the real-time data acquisition system:
a) BACnet reader utility. This actor was developed by Lawrence Berkeley National Lab (LBNL, 2011) which reads data from BACnet compatible BEMS systems. To use it, the user needs to specify an XML configuration file which is composed of BACnet point list in a fixed format, and then the connection between the data acquisition computer and the BMS computer is established.
b) StoreBACnetDatatoBIMDatabase. This actor is used to convert the raw data into Structured Query Language (SQL) statements that can then be sent to the database actor. This transition actor requires a data point description file in .csv file format, which should includes the names of all the data points. During the runtime, it finds in the 'operationaldata' table a record with exactly the same name, and retrieves its data point index, its physical type (temperature, velocity, etc,) and its operational type (sensor, set point or control signal).
c) DatabaseManager. This actor is used to establish the connection between BCVTB and BIM-based database, 'SQLStatement' actor is applied to execute any valid SQL statements in this project, which inserts the real time operational data into multiple sensor, control signal and set-points tables.

Application Layer

Besides the development of the core layer, we also investigate the application layer of this integrated infrastructure. The examples in the application layer in this study are building reference models, energy visualization and energy diagnostics, which are described briefly in the sections below:

1) Building Reference Model

A whole building model is developed in MATLAB (MATLAB, 2011) which simulates the building envelope, HVAC, lighting, and building control systems. It takes the design information directly and automatically from Revit architectural (e.g., geometry, location, orientation, room information, floor and roof information, material information) and mechanical drawings (zones, terminal units and AHUs). The Revit architectural and mechanical drawings represent the "design-intent" model, where all information is based on the design documents and as-built drawings. The actual operational information such as HVAC control sequences are drawn from the conversations with building facility team. Real-time weather data is available in from onsite weather station.

In addition, the model represents "plug loads" which includes desktop computers and any other electrical equipment used in buildings. The baseline data is from available documentation. However, onsite observations for plug devices were also conducted. Through this, the model considers both direct electrical energy use and its effect on the internal heat gains. The occupancy profile is based on the internal load estimation (O'Neill et. al., 2011).

a) Building Envelope Model

The building envelope model is developed in MATLAB based on the 3R2C thermal network model (ASHRAE Fundamentals, 2010).

b) Building HVAC Model

The steady-state lumped HVAC system and equipment models are developed in MATLAB. Model structures and functions are similar to those used in EnergyPlus (EnergyPlus, 2011).

2) Energy Performance Visualization Dashboard

Current building energy management systems can provide facility managers (FMs) with a rich set of building operational data, which include system and equipment performance (temperature, pressure, air flow rate, status, energy usage, etc.), control signal and status, equipment alarms and indoor environment quality (e.g. CO_2 level). However, the gap is how FMs can best use those data to maximize the benefits of building operation. An interactive user interface was developed for FMs to explore available data to improve building operation and their decision-making. The energy performance visualization dashboard aims to enable: 1) visualization of energy-related metrics at different building and HVAC systems levels; 2) comparisons between measured quantities and predictions derived from the integration of physics-based modeling methods; 3) energy fault diagnostics and classification to aid in decision support targeting of root cause analysis; and 4) identifying persistent trends in energy usage.

3) Energy Diagnostics

The energy diagnostics method applied in this study is based on the statistical process control (Chiang, et al., 2000) and rule based methods (NIST APRA rules for AHUs, Schein et al., 2007)

CASE STUDY

The proposed infrastructure is implemented in building 7114, at Naval Station Great Lakes, Great Lakes, IL.

Building Facts

Building 7114 is a 149,875 ft^2 recruit barracks. It is a long rectangular building, consisting of a large block of berthing compartments, heads (bathrooms), laundry rooms, classrooms, a quarterdeck with a two-story atrium and office spaces, and a large cafeteria/galley as shown in Figure 14.

Figure 14 Building 7114 at Naval Station Great Lakes

The recruits leave the barracks for drills and marches and during personal time on Sunday and holidays. Building 7114 shares the absorption chillers, cooling tower, heating hot water heat exchangers, chilled water pumping system, heating hot water pumping system, and the condenser water pumping system with another similar building. The compartment area is served by two variable air volume (VAV) Air Handling Units (AHU) with VAV terminal units (with hot water reheat). Four classrooms, quarterdeck and dining area are served by another three AHUs. When Building 7114 is occupied by recruits, the building is occupied 24 hours a day for seven days a week. Recruits spent about 85% of their time in the barracks. A distributed DDC control system is installed in Building 7114. This system monitors all major lighting and environmental systems. Operator workstations provide graphics with real-time status for all DDC input and output connections. Additional power sub-meters and thermal BTU meters were installed and integrated with existing building BMS.

Real-time Implementation of the Infrastructure

The real-time implementation of the integrated infrastructure in Building 7114 includes two desktops, one is running Siemens BMS system and the other one is running the proposed system. The infrastructure is set up in a Linux machine with RedHat 5.5 Enterprise operation system. Data acquisition, building energy modeling, energy visualization and on-line FDD are running simultaneously.

The real-time energy dashboard includes four visualizations that display various aspects of how energy usage is distributed across different end uses (lighting, pumps, plugs, fans etc.) in the selected time period.

- Display the "Current Power" energy breakdown at any given time instant.
- Displays the power breakdown at the time-step corresponding to peak overall power consumption during the selected time period
- Display the breakdown of total energy usage of selected time period.
- Display the real-time power breakdown over the entire selected period.

Real-time Energy Simulation Results

An energy model integrating building envelope and HVAC system is built up to simulate real-time energy consumption, driven by real time weather conditions. This model has 143 zones including compartments, classrooms, corridors, dining room and attic spaces. Over 100 VAV boxes, 20 terminal reheating coils, 5 AHUs and two absorption chillers are modeled. Air loop and water loop are strongly coupled to make sure the supply side and air side demands balanced. The integrated model is calibrated offline based on real-time data. Figure 15 shows the building level chilled water side load comparison between simulated and measured ones. 85% of the time differences are within +/-10%.

The calibrated model is then running continuously on the onsite Linux machine with 5 minutes simulation time-step and stores the data back into the BIM-base database.

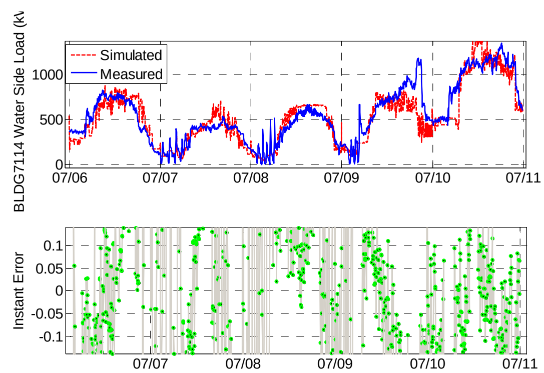

Figure 15 Building 7114 Real-Time Simulation Results from 07/06/2011 to 07/11/2011.

Real-time FDD

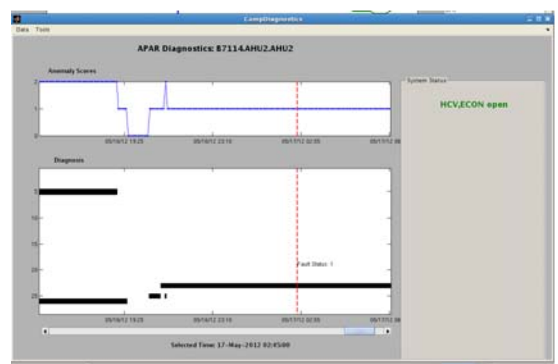

Figure 16 A snapshot of AHU diagnostics based on NIST APAR rules (fault heating coil valve and economizer open at the same time)

Machine learning and rules based FDD approaches are implemented in this study. Figure 16 shows a screenshot of the AHU diagnostics tool implementing NIST APAR rules. The bottom plot indicates the rules that were violated and the top plot indicates how many rules were violated. The tool has been implemented to support energy impact analysis that is accessible as menu items in the top. The tool also enables one to visualize the raw data. AHU economizer related faults were successfully detected, diagnosed and fixed on the demonstration site. Other identified faults include sensor drifting, stuck VAV box damper, and VFD malfunctioned etc.

CONCLUSION

This study has demonstrated a real-time integrated infrastructure which integrates a relational database, and data acquisition to support online building simulation, energy visualization and FDD in a real building. There are a few observations and lessons:

- A real-time connection between a BEMS vendor machine and our DAQ machine is established through an Ethernet cable. However, the total number of data points is limited by 1) bandwidth of vendor BEMS system, 2) the data exchange communication protocol (BACNet) that BEMS complies with. 3,000 data points are feasible for a 5-minute sampling frequency in this study.
- With the fast growing database, the query time for data points degrade, which affect the real-time energy visualization. An optimized query based on a binary search tree was developed and implemented.
- Mapping BEMS points onto each HVAC component is still a manual process. We must identify each measured point and map it back into the HVAC system diagram. An auto-mapping tool would speed up the DAQ process.
- Alternative solutions were developed to overcome the limitations of Revit Mechanical software which does not support translation of a HVAC zone to an IFC zone. Future development should focus on the open source of Revit IFC translator.

ACKNOWLEDGMENT

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LIST OF ABBREVIATIONS

AEC	Architectural, Engineering, Construction
AHU	Air Handling Unit
BACnet	A Data Communication Protocol for Building Automation and Control Networks
BEM	Building Energy Modeling
BEMS	Building Energy Management System
BCVTB	Building Control Virtual Test Bed
BIM	Building Information Model
BIMTB	Building Information Model Test Bed
DAQ	Data Acquisition
FDD	Fault Detection and Diagnostics
IFC	Industry Foundation Classes
MVD	Model View Definition
SQL	Structured Query Language
VAV	Variable Air Volume

REFERENCES

ASHRAE. 2008. BACnet--A Data Communication Protocol for Building Automation and Control Networks. ASHRAE.

Chiang, L., Russell, E. and Braatz, R. 2000. Fault Detection and Diagnosis in Industrial Systems, *Springer Verlag*, London.

EnergyPlus. 2011. EnergyPlus Engineering References. Department of Energy.

Graphisoft, http://www.graphisoft.com/. 2011

Lee, S. Uk, Painter, F. L. and Claridge, D. E. 2007. Whole-Building Commercial HVAC System Simulation for Use in Energy Consumption Fault Detection. *ASHRAE Transactions*, v113, part2: 52-61.

MATLAB, 2011b. MATHWORKS, 2011.

Schein, J., Bushby, S. T., Castro, N. S., House, J. M. 2007. Rule-Based Fault Detection Method for Air Handling Units. *Energy and Buildings*, Vol. 38, No. 12, 1485-1492.

Thornton, B.A., Rosenberg, M.I., Richman, E.E., Wang, W., Xie, Y., Zhang, J., Cho, H., Mendon, V.V., Athalye, R.A., Liu, B. 2011. Achieving the 30% Goal: Energy and Cost Savings Analysis of ASHRAE Standard 90.1-2010. PNNL-20405; Other: BT0703000. Richland, WA (US): Pacific Northwest National Laboratory (PNNL). 368 pp.

Thierry, N.S., Wetter, M. Li, Z.W., Pang, X.F., Bhattacharya, P., and Haves P. 2011. BACnet and Analog/Digital Interfaces of the Building Controls Virtual Test Bed. *In Proc. of the 12th IBPSA Conference*. Sydney, Australia, 2011.

Wetter, M. 2011. Co-simulation of building energy and control systems with the Building Controls Virtual Test Bed. *Journal of Building Performance Simulation*, Vol.3(4).

O'Neill, Z. D., M. Shashanka, X. Pang, P. Bhattacharya, T. Bailey and P. Haves. 2011. Real Time Model-based Energy Diagnostics in Buildings. *The 12th International Building Performance Simulation Association Conference and Exhibition*. Sydney, Australia. November 14–17, 2011.