A software approach for combining real time data measurement and building energy model to improve energy efficiency

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Smart Building team Capstone project report

(Do not Circulate)

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Abstract

In this paper, we introduce an innovative software approach for building energy efficiency analysis. It takes real-time data from meters and sensors in the building, analyzes energy usage, and helps building managers to save energy.

Buildings consume 40% of the $370 Billion annual energy cost in U.S., and 30% of energy consumption is wasted. Existing building control systems waste energy because of old HVAC (Heating, Ventilation and Air Conditioning) equipment, lack of maintenance, over-cooling, over-ventilation and other reasons. More and more sensor nodes are deployed in the building for energy monitoring, but the large amounts of data generated are not fully utilized. On the other hand, building scientists use energy models to do energy efficiency analysis, but the models they use are not accurate and it takes a long time to develop a full model.

By combining real time data and EnergyPlus[1] model, we provide an accurate and self-adaptive software approach for energy analysis and prediction. With an accurate building model, we select different energy efficiency solutions, compare the results, and provide a recommendation for building mangers to save energy. We use Sutardja Dai Hall, a real building on Berkeley campus, as our test bed in the project. After energy analysis on the building model, the software recommends several energy efficiency scenarios and the simulation result that would predict energy savings for each scenario. This paper shows the viability for this software approach for one building, and further research might be able to extend the work to other buildings.

Keywords: energy efficiency, real time data, building model

1. Introduction

Buildings consume 40% of the $370 Billion annual energy cost in U.S., and 30% of energy consumption in building is wasted. Nowadays, many buildings have thousands of sensors and meters installed, but they are not fully utilized to achieve energy efficiency. Existing building automation systems are not sophisticated enough to discover energy wasting problems. Meanwhile, the existing building model technique has always suffered from lack of accuracy so that any analysis or prediction based on inaccurate building model is not reliable.

This paper introduces a technology that combines the real time building data with EnergyPlus model and provides a software tool for building managers to perform accurate energy efficiency prediction based on an accurate model, which is calibrated by real-time data generated from the building. The software lays on the top of existing Energy Management System and Building Automation System and retrieves real-time data through the existing communication protocol

The testbed building we use is Sutardja Dai Hall, a 7-floor office building with a nanofabrication lab which has 800kw average power consumption. We get real-time data from sMap(Simple Measurement and Actuation Profile)[2], which gets data from Siemens Apogee system[3]. The entire process, including data retrieval, analysis and simulation, is done by software automatically. We get electric power consumption of lighting and plug loads to calibrate the electricity usage in the model and using historical data of HVAC equipment to calibrate the performance curve. We minimize the difference between the simulation result and the actual measurement to make the model accurate for analysis. Furthermore, a list of predefined energy efficiency scenarios are compared and simulated to predict the cost and potential savings. The user could also select customized options to simulate in the model.

The second section of the paper introduces some background knowledge and tools that we use, including sMap, EnergyPlus, and HVAC system of Sutardja Dai Hall. The third section talks about the method we use to refine and calibrate the generic energy model. The fourth part introduces the graphic user interface and several extended functions on the calibrated model, which is aimed to help building managers to improve energy efficiency.

Our work assumes that the building has a central energy management system with real-time data measurement and a general EnergyPlus model. Those are two prerequisites of our work. In the future, we want to expand our tool to other buildings and add a function to generate a model.

2. Background

2.1 sMap(Simple Measurement and Actuation Profile)

sMap is a protocol on the top of existing building energy management system, from which we get all of the data in the building. The website (http://new.openbms.org/plot/) shows an interactive interface for users to plot time series data for visual display. sMap gets the real time data through different communication protocols within different buildings, and keeps all data in its database. Besides this interface, we can also retrieve the JSON-format data from the API provided by sMap. All the measurement data we include in this paper is from sMap.

2.2 EnergyPlus

EnergyPlus is a comprehensive building model software developed by DOE. It simulates the thermodynamic process, heating and cooling loads, and energy usage over different time periods in a building. The input of EnergyPlus, IDF file, is a text file that describe all the information for a building, including the building envelope, square feet, HVAC equipments, lighting and plug loads. The original EnergyPlus model for Sutardja Dai Hall is developed by Rongxin Yin, a building science researcher in LBNL. All the work described in this paper uses EnergyPlus as the modeling software and the original model as the basis for calibration, analysis and prediction.

2.3 Sutardja Dai Hall

Sutardja Dai Hall is a 7-floor building on UC Berkeley campus, consisting of a nanofabrication lab and an office building. The HVAC system of Sutardja Dai Hall includes chiller, cooling tower, air handling unit(AHU), variable air volume(VAV) box and reheating coil. It has a Siemens Apogee Energy Management System[3] controlling the HVAC equipment and sensors, monitoring temperature, humidity, air flow rate, valve position, electric power and other measurements. The average electricity consumption of the whole building varies from 800kw to 1000kw. All our research is done related with this building, and one of the purposes of our project is to help the building manager to reduce energy waste while maintaining occupancy comfort.

3. Methodology

3.1 Auto-calibration

Building models are used for energy analysis and prediction, but the problem with the previous model is that it is not accurate so that the result of simulation is not reliable. Traditionally, building scientists calibrate the model manually by taking utility bill information and equipment data sheet from the manufacturer, which is time consuming and require expertise knowledge. We speed up this process by automatically calibrating the model using a software approach.

3.1.1 Lighting and plug loads calibration

We get the sensor and meter data from the building through sMap using database queries. The first step of calibration is to match the real world data point with the corresponding parameters in the model.

The granularity of control element in EnergyPlus model is zone, which is composed of several adjacent rooms and defined when the initial model is created. In the real building, the granularity of data and control is different for different parameters. Lighting power and plug load power have floor-level meters and the VAV system in HVAC has the zone control granularity, which is different from the zone in the model.

For the lighting power calibration, after getting the real time data of lighting power per floor, we need to divide the whole floor data into zones for EnergyPlus. I first take the number of rooms on each floor, the square feet of each room, and then match the relationship of each room to each EnergyPlus zone. Then, I divide the lighting power per floor by the total square feet to get the average power for each square foot, and multiple the value with the square feet of each zone to estimate the zone-level lighting power. This method is not accurate in terms of room-level power, because each room has a different lighting schedule and different occupancy loads. However, we are not able to get the accurate lighting power of each room since there is no room-level lighting power meters. If the building does not have floor-level meters, we have to use the whole building electric meter to divide the total building square feet number which is even less accurate. For plug loads, the process is the same with lighting because we only have floor-level measurement for plug loads. Because the lighting and plug loads power is repetitive for the day of the week, we calculate the average value for each hour in one day and take it as the estimation of power consumption.

After calculating the power consumption for each zone in the model, I converted it into a percentage of maximum power consumption and put the percentage value into the schedule of lighting and plug loads in EnergyPlus. The comparison of lighting power between model and real building is shown in figure 3.1. It is the second floor lighting power comparison between real time data (grey), simulation result before calibration (blue), and simulation result after calibration (red) in November 2011.

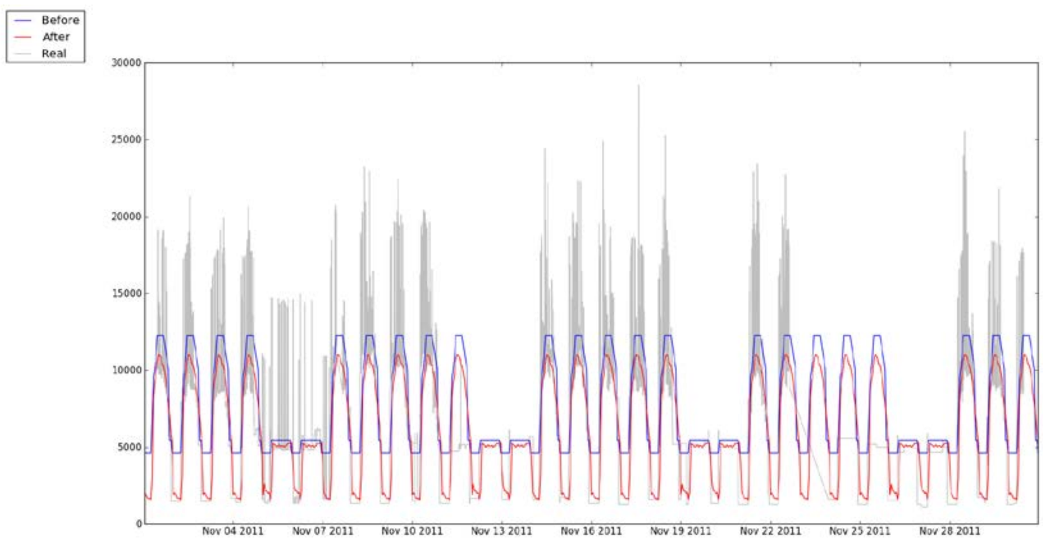

Figure 3.1 Lighting power comparison for the second floor in Sutardja Dai Hall, November

3.1.2 HVAC calibration

The HVAC system in Sutardja Dai is composed of several components including Variable Air Volume (VAV) box, Air Handling Unit, pump, chiller and cooling tower. For VAV, we calibrate the heating/cooling set-point schedule. The process is similar to the lighting calibration, we find the matching relationship between the actual VAV zone with the zone in the model and then convert the data into a schedule.

For the AHU fan, pump, chiller and cooling tower, we calculate the curve and its coefficients using algebra regression of real data to calibrate the default value in the model.

$$FPR = C_1 + C_2(AFR) + C_3(AFR)^2 + C_4(AFR)^3$$

FPR = Fraction of the Design Fan Power & AFR = Fraction of the Design Air Flow Rate

For example, the equation for the supply fan in the AHU is a cubic function that describes the input of fan power and output of air flow. The coefficients represent the performance and efficiency of the fan, which changes over time. For old HVAC equipment, the performance is not as good as a new one, so it's not accurate to use the coefficients from the manufacturer to describe it in the model. Our software calculates the current coefficients from the real time data, puts it into the model, and makes each specific equipment more accurate.

3.1.3 Model Accuracy

After the above calibration step, we found the model accuracy of the total building power to be 3.8%, which is calculated using the following equation.

$$accuracy = \frac{\sum(Measured - Simulation)}{Time} \times 100\%$$

We use the real time data in April 2012 to calibrate the model, and compare the simulation result with the actual building electricity consumption. As shown in figure 3.2, the simulation result is a little higher than the actual data because 700 kw of the total 1000 kw is from the nanofabrication lab, which is not calibrated. If we just calculate the accuracy for the office part of the building, the model accuracy would be better.

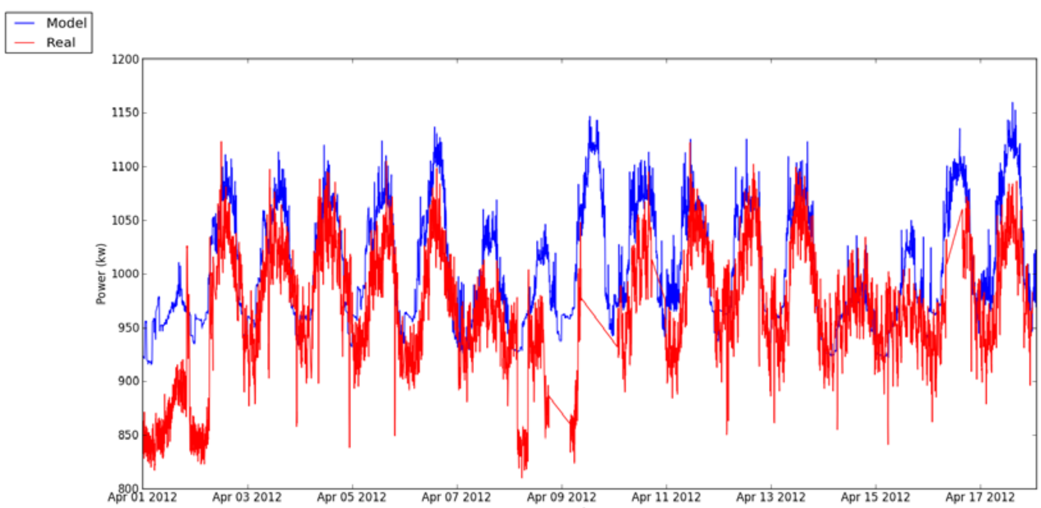

Figure 3.2 Comparison of whole building electric between simulation result and real data

3.2 Energy Efficiency Scenario Analysis

After the model is calibrated, we use it to evaluate different energy efficiency scenarios that would save energy for the building. The advantage of doing this is that there is no risk of changing control parameters in the model, and user does not need to worry about the side effects of implementing the scenario in the real building. With the calibrated and accurate model developed by the previous steps, the simulation result would help our users to make the decision whether the scenario should be implemented in the real building.

Here is the list of possible scenarios we want to simulate in the model.

Name	Description
Light Bulb replacement	Replace the fluorescent bulb with low-cost LED
Digital Lighting Switch	Install digital lighting switch with occupancy sensor to cut unnecessary lighting
Digital Thermostat	Install digital thermostat with wireless control to make cooling/heating more efficient
Pre-cooling	Adjust the set-point of HVAC to shift Cooling demand from peak period to non-peak period
VFD(Variable Frequency Driver) retrofit	Install VFD on fan system to improve efficiency
Window Shading	Add shading to the window to avoid direct sunlight and reduce corresponding cooling load

Most of the energy efficiency and demand response scenarios could be simulated within the model, but most building managers do not know how to use EnergyPlus. We design an easy-to-use interface by encapsulating the process of editing the input file, running EnergyPlus, and analyzing the output.

Let's take pre-cooling as an example to show how to simulate a scenario in the model. The purpose of pre-cooling is to shift the peak demand in the afternoon to the morning, and the method is to adjust the set-point to achieve this goal. The schedule of VAV set-point is already calibrated from the real-time data. In order to pre-cool the building, we set down the set-point by 2 degrees from 8am to 12pm and then set up the set-point by 2 degrees from 12pm to 5pm. By doing this, we use the building thermal mass to store the cooling energy by pre-cooling the building in the morning and lower the power demand in the afternoon. The result of pre-cooling in November 2011 is shown in the figure 3.3.

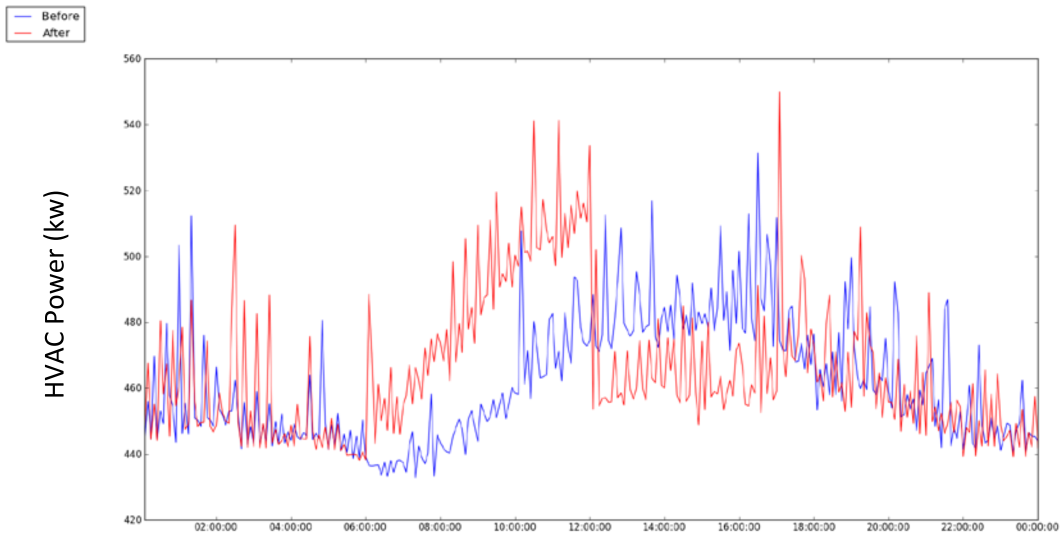

Figure 3.3 Comparison of pre-cooling for the HVAC power consumption

In the Graphic User Interface part(section 4), we have a customized input for users to define the set-point of pre-cooling and the corresponding time. Pre-cooling could also be used for demand response event in the summer, which will reduce the peak demand. In winter, although the outside temperature is low, the HVAC is still cooling the building most of the time because of the insulation and internal heat loads.

3.3 Rate Schedule Integration

Utility companies in California have different rate schedules for different commercial buildings, and we want to show not only the energy consumption but also the cost to our users so that they can make a financial analysis. For many building owners who are not energy experts, they concern more about the money spent rather than the energy consumed. For some time-of-use rate schedules, the cost of energy could be quite different based on a different time period. We provide a module that could convert energy consumption into the cost given the rate schedule from any utility company.

This module takes the output variable 'Electricity:Facility' in EnergyPlus, which simulates the electricity power for each time step. We calculate the energy for discrete time stamps and multiply by the rate for the corresponding time of the day and day of the week. We take A_6 rate schedule of PG&E(Pacific Gas and Electricity), which is used for large commercial buildings having power consumption higher than 200kw. In A_6 rate, the cost per kw in summer peak time is much higher than during non-peak time, and it makes the pre-cooling method effective to save money. We did not use the actual rate schedule for Sutardja Dai Hall which is different from A_6, because university buildings have a complicated rate and we assume that it is a regular commercial building.

3.4 Graphic User Interface

The Graphic User Interface is an important part of our software, because it shows the input and output to the building managers and helps them to make decisions on how to operate the building.

We build a web-based interface for the software so that the user can use it through browsers from any platform. It's a SaaS(Software as a Service) based architecture that hosts all the software and data on the cloud. The reason why we put it on the cloud is because it takes a lot of time and resources for the simulation and data retrieval. The powerful computation ability on the cloud sever will shorten the response time and improve the user experience. With high speed Internet access, the data transmission between client browser and sever takes little time, so the speed is much faster than local computation. However, one concern of a SaaS based product is that it might be difficult for building managers to upload all the data into our cloud server, and the privacy concern might block some of our users.

The web interface is shown in figure 3.4, we have eight functions for the user: equipment calibration, approximate future usage, access past projects, EnergyPlus model, explore future alternatives, red flag detection, check model accuracy and real time data. Before having this interface, we assume that we already have the real-time data from the building and a generic EnergyPlus model.

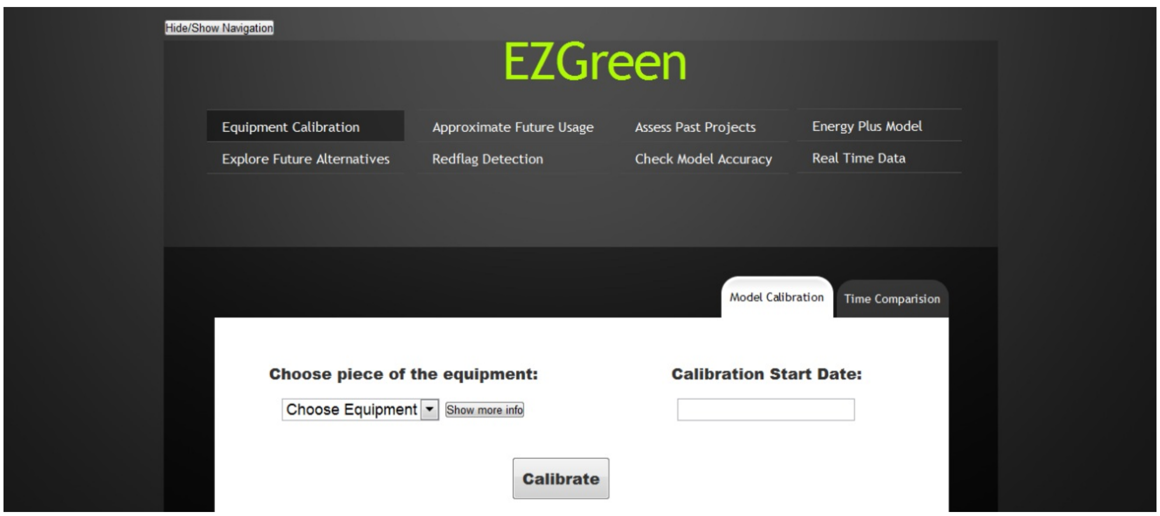

Figure 3.4 Graphic User Interface of our software

Equipment Calibration: The calibration of HVAC equipment including supply fan, return fan, chiller, and cooling tower is described here. User could choose the equipment and the date he wants to calibrate and our software will show the current coefficients in the model, the calculated coefficients using real time data, and the comparison of performance curve with two sets of coefficients.

Approximate Future Usage: This part will run the simulation for a future period and calculates the energy consumption and cost for the building manager.

Assess Past Projects: This feature allows the user to track savings of projects implemented in their building. They can identify when they implemented a specific project and a timeline will be provided to show them the changes in their energy costs before and after they implemented a project.

EnergyPlus Model: The text input of EnergyPlus is displayed here. User can browse the detailed information of the model and download it for other use.

Explore Future Alternatives: The features of this tab are to allow the user to run various simulations in the calibrated EnergyPlus model to identify potential energy saving scenarios. We only supply four basic strategies, but ideally the user could simulate through a long list of potential ideas. The user identifies a simulation time period and then a simulation is performed on the calibrated model and compared to the expected energy usage to calculate the potential energy and cost savings as well as the payback for a specific project.

Red Flag Detection: Red Flag Detection can be used to detect anomalies or violations of comfort standards in the building. We provide a few basic options such as checking to see when a zone temperature goes too far above or too far below the set-point, checking when the building exceeds a certain power level, and checking what the maximum lighting and plug loads are at night. We also want to provide the user the option to build up their own custom alarm where they could select any of the data streams provided by sMAP and create their own custom alarm equation.

Check Model Accuracy: In this tab, user can select a time period to run the simulation, and check the accuracy of the model.

Real Time Data: This tab allows the user to get a look at the data streams that describe their building. In our case, we provide a link to sMAP, the tool used to gather and store the data collected from the building.

4. Literature Review

4.1 Energy Model

Building science researchers have been using EnergyPlus models to simulate demand response for a long time. Several studies by Demand Response Research Center in LBNL(Lawrence Berkeley National Lab) showed the process of using a calibrated EnergyPlus model to simulate several demand response strategies including pre-cooling[4][5]. They built a generic EnergyPlus model using DRQAT[6], a software that generates an EnergyPlus model by basic building information, and then calibrated the model manually.

For a study for 8 office buildings in California, they use monthly whole building power to calibrate and refine the model, and finally make the model accuracy within 10%.[4] Because the buildings only have a total building electricity meter, the meter data in extreme cold weather are used to estimate the lighting and plug loads. They do not have the occupancy schedule either, so the model parameters are readjusted according to the internal heat loads after the initial calibration to match the simulation result and real building consumption. Several demand response strategies are simulated in the calibrated model, and the simulation predicts the actual experiment result well. Another study also used EnergyPlus to evaluate demand response in a building on UC Merced campus, and got the prediction accuracy within 10%[5].

Our project is different from them because we use a software approach to refine the model automatically and continuously. Traditional model development and calibration takes time and energy expertise, and may not be scalable to other buildings.

4.2 Real-time data measurement

The wide use of wireless sensors and digital control equipment in the building enables huge amounts of data generated. Traditionally, different building HVAC equipment vendors use different communication protocols. Some studies have been done to provide a common interface for application to get physical data easily. sMap[1] is designed to be a prototype of universal interface encapsulating sensor networks with other building equipment data sources, so applications could focus on their functionality.

Other studies in wireless sensor network applications in buildings have shown the viability of deploying sensors in large scale to monitor the energy usage and thermal comfort. Zigbee[7] is the industry-standard protocol for WSN application. A study showed that Zigbee based sensor network is easy to deploy and maintain in the building for energy monitoring[8].

The trend is that more and more sensors would be deployed in the building, hence more data would be generated. The real challenge is how to utilize the data generated to achieve better energy efficiency. Our work suggests one way to use the data – to combine it with EnergyPlus model to help building managers to save energy.

5. Conclusion and future impact

This capstone project shows the viability of a unique software approach of combining building model and real time data to analyze the energy efficiency. Prior to this project, we assumed that the building should already have sensors/meters installed and a generic EnergyPlus model developed. We link these two resources together and utilize them for analysis and prediction.

The most obvious weakness of our work is that the tool could only be used in one building. The next step of future work would be to make the tool adaptive to other buildings as well. The challenge is that different Building Energy Management System have different communication protocols, and it might be difficult to make one interface for different protocols.

Another shortcoming is that our tool relies on the assumption that the building has real-time data access and an EnergyPlus model. The current situation is that many existing buildings do not have a fully digital control system or wireless sensor network deployed, and they do not have a generic EnergyPlus model either.

6. Future work

We suggest two parts of future work that would be valuable.

One is to make the existing software tool adaptable to other buildings with real time data and EnergyPlus model. After the portability is proved, the tool could be adaptive to any other modern buildings and help them to improve energy efficiency.

The other possible idea is to develop a software tool that could build an EnergyPlus model for any building from scratch. DRQAT[6] is developed to generate a generic EnergyPlus model quickly, but the model is not accurate nor specific. To combine the model generator and our work would be useful for buildings without a pre-developed EnergyPlus model.

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