CAMPUS-WIDE INTEGRATED BUILDING ENERGY SIMULATION

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ABSTRACT

Effective energy management for large campus facilities is becoming increasingly complex as modern heating and cooling systems comprise of several hundred subsystems interconnected to each other. Building energy simulators like EnergyPlus are exceedingly good at modeling a single building equipped with a standalone HVAC equipment. However, the ability to simulate a large campus and to control the dynamics and interactions of the subsystems is limited or missing altogether.

In this paper, we use the Matlab-EnergyPlus MLE+ tool we developed, to extend the capability of EnergyPlus to co-simulate a campus with multiple buildings connected to a chilled water distribution to a central chiller plant with control systems in Matlab. We present the details of how this simulation can be setup and implemented using MLE+'s Matlab/Simulink block. We utilize the virtual campus test-bed to evaluate the performance of several demand response strategies. We also describe a coordinated demand response scheme which can lead to load curtailment during a demand response event while minimizing thermal discomfort.

INTRODUCTION

Demand Response (DR) programs are designed to induce changes in electric usage by end-use customers from their normal consumption patterns in response to signals from the utility company. However, most current DR strategies are reactive Motegi et al. (2007). These strategies are often rule-based and do not take into account the load dynamics and interactions of demand-side and supply-side systems within a campus. By not considering the load dynamics and the weather and disturbance forecasts of the system, canned DR strategies often run the risk of causing high discomfort for occupants in the case of a demand response event. Under certain operating and curtailment conditions, large kickbacks may occur in the power consumption of the campus towards the end of the DR event when systems are returned to their nominal operating conditions. DR strategies must therefore be proactive by considering current and forecast operating conditions and curtail power while minimizing the level of discomfort and magnitude of kickbacks.

The capability to control set points at on the demand-side (i.e. buildings, equipment, production systems) and chiller plants is usually under the management of centralized campus facilities. Currently, a significant initial financial investment is required to equip the campus with the capability of supervisory control to evaluate the efficacy and safety of campus-wide DR.

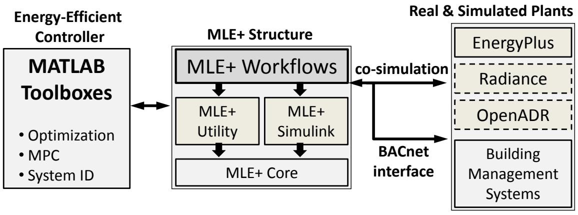


Figure 1: MLE+ Matlab-EnergyPlus co-simulator

Campus-wide simulations present a low-cost means for evaluating different control strategies from the demand-side, supply-side and coordinated control across multiple campus-wide sub-systems. Unfortunately, implementing a full scale campus level simulation for control purposes is a challenging task with existing tools. For example, the whole building energy simulator EnergyPlus provides a large library for physical building models and chiller plants. However the accuracy and the control capability of many built-in subsystems are not suitable for advanced control. The main reason for this is that EnergyPlus does not provide a modular design for large-scale modeling and simulation, the kind which is suited for a campus-wide building energy simulation. For instance, it is non-trivial to simulate shared resources between the supply and demand side with EnergyPlus.

We have developed MLE+ Bernal et al. (2012), an open-source Matlab/Simulink toolbox which allows co-simulation with EnergyPlus. In this paper, we illustrate the use of MLE+ for campus-wide control system and building modeling and simulation with a focus on demand response issues. This paper has the following contributions:

1. Using MLE+ we extend the capability of EnergyPlus to simulate a large campus in a modular fashion. The campus consists of multiple buildings on the demand side and a common chilled water resource, such as a central chiller plant, on the supply side.
2. We evaluate multiple demand response strategies at a campus level and characterize their performance.
3. We propose and empirically evaluate a coordinated supervisory demand response strategy which can curtail during a DR event while minimizing the adverse effects of curtailment such as discomfort and kickbacks.

Organization: We briefly introduce the capabilities of MLE+ followed by a description of how it is used in conjunction with EnergyPlus to simulate an entire campus. We then present a case study in which we evaluate the performance of several demand response strategies at a campus level. We conclude the paper

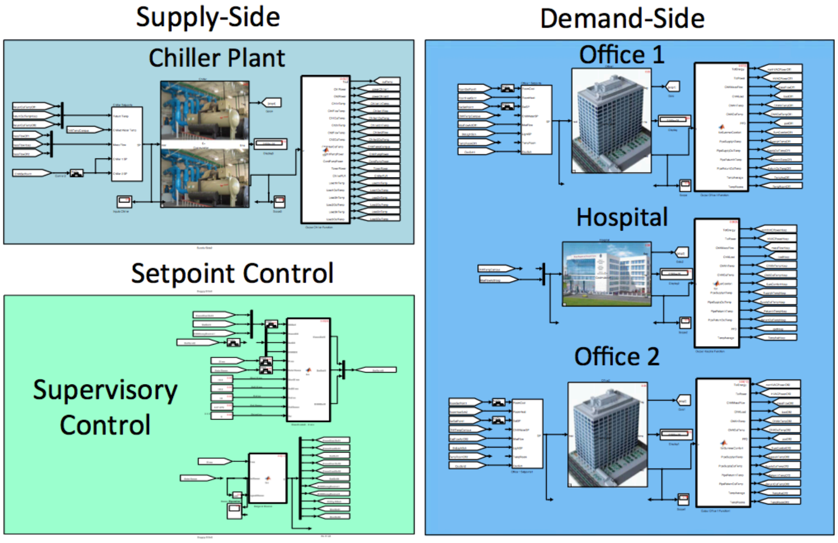
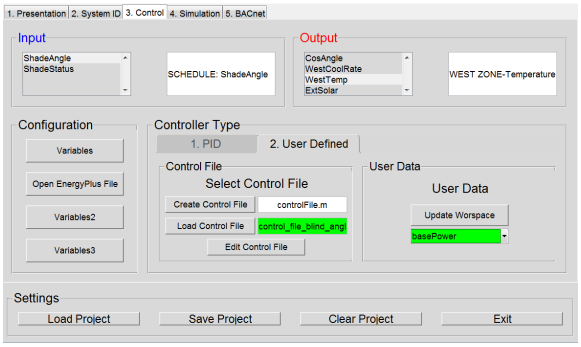


Figure 2: Campus cooling water loop

following a discussion on related work and the use of the free and open-source MLE+ toolbox.

MLE+: Key Features

MLE+ is an open-source Matlab/Simulink toolbox for building energy modeling and interfacing with advanced controls (Fig. 1). MLE+ provides the capability to perform co-simulation with EnergyPlus from Matlab. Co-simulation (or co-operative simulation) is a simulation methodology that allows individual components to be simulated by different tools running simultaneously and exchanging information in a synchronous manner.



Input
ShadeAngle
ShadeStatus
SCHEDULE: ShadeAngle

Output
CosAngle
WestCoolRate
WestTemp
ExtSolar
WEST ZONE-Temperature

controlFile.m
control_file_blind_angl
basePower

Figure 3: MLE+ tool interface

The following are the main features of MLE+:

1. **Simulation configuration**: The MLE+ front-end (Fig. 3) streamlines the configuration process of linking the building model and the controllers by abstracting the necessary parameters from the co-simulation. This reduces setup time and configuration problems.
2. **Controller design**: MLE+ provides a control development workflow as well as graphical front-ends for designing advanced control strategies, in which the building simulation is carried out by EnergyPlus while the controllers are implemented in Matlab or Simulink.
3. **Simulation-based optimization**: MLE+ can be used to find optimal parameters or control sequences for building system simulations in EnergyPlus.
4. **Data analysis**: After a co-simulation run, using MLE+, the output data from EnergyPlus can be aggregated, analyzed and visualized in Matlab.
5. **Building Management System Interface**: MLE+ provides a BACnet interface to develop and implement control methods for real building equipment.
6. **Matlab environment**: MLE+ allows complete access to the Matlab environment and toolboxes such as Global Optimization Toolbox, System Identification Toolbox and Model Predictive Control Toolbox. The user can step through the code for debugging and pause the co-simulation at any time.

2 MLE+: Campus Wide Simulation

MLE+ allows you to connect multiple buildings modeled in EnergyPlus and simulate campus-wide dynamics. Each EnergyPlus file correspond to a single building. This helps keeping the system modular and allows to redesign/calibrate the models individually. This section discusses the MLE+ implementation how to connect multiple buildings through a chilled-water loop or hot-water loop. We have put together a simplified campus and show some results in Section 2.5.

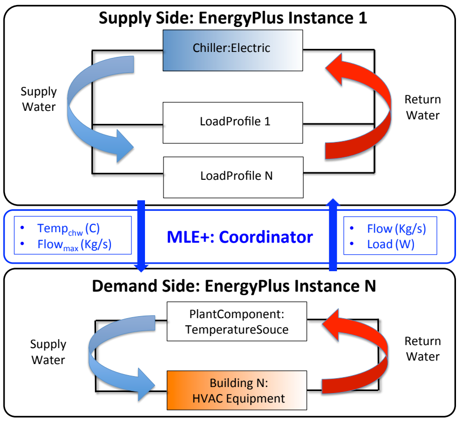


Figure 4: MLE+ configuration for Demand-Response modeling.

The basic campus configuration consists of an Chiller/Boiler plant that supplies chilled/cold water to multiple buildings on the campus. Figure 4 shows this setup where we can distinguish two portions: the supply-side equipment and the demand-side loads. We divide the campus in this manner in the same manner that EnergyPlus simulates its loads: the supply-side equipment is trying to provide the demand-side part with the necessary load, power, energy to meet its setpoints. We are employing the same principle in MLE+ to simulate these two interacting parts. The demand-side requires certain chilled-water flow rate, heat extraction/addition according to its current setpoints and conditions. MLE+ exchanges this information between the supply-side and demand-side EnergyPlus files.

The buildings return the warmer water after it has circulated through its heat exchangers (cooling coils). The electric chiller cools down the returned water from the buildings to a specified setpoint. The chiller plant control loop maintains the temperature of supply water while the buildings' HVAC equipment rejects heat into it. Here the building' equipment aim at maintaining comfortable conditions of its multiple zones. Figure 4 shows the different equipment most commonly used in the water loop system.

2.1 EnergyPlus/MLE+ Implementation

To model the previous system, we have modeled all the system components in multiple EnergyPlus files, one for each building and one for the chiller plant. We can distinguish two types of files, the supply-side EnergyPlus files, corresponding to the Chiller plant, where it supplies the necessary chilled water (flow rate and temperature), and the demand-side EnergyPlus files, where the buildings and their HVAC equipment is modeled. The demand-side checks the zone temperature setpoints and decides on how much flow rate (at the current water temperature) is needed to achieve the room's air setpoints. For this example, we only have one supply EnergyPlus file (only one chiller, however, we could include multiple ones in series or in parallel) and two demand-side Energyplus files (only considering two buildings). For clarity and conciseness, Figure 4 only shows two EnergyPlus instances: one chiller and one building.

2.1.1 Supply-Side

The EnergyPlus **LoadProfiler** object is used to model the buildings demand on the supply-side file. This object represents the building and its HVAC equipment. The **LoadProfile** object represent the demand for water flow rate and the power load at every time step. The power load is the amount of heat (Watts) that gets dumped into the water flow. These parameters are set through MLE+ at every time step of the simulation.

2.1.2 Demand-Side

The **TemperatureSource** object is used to model the Chiller supply on the building files. This object represents the Chiller, specificallly, the water flow rate and intake temperature. The **TemperatureSource** object sets the water flow rate and the power load at every time step. These parameters are set through MLE+ during simulation according to the needs of the Supply-side file.

MLE+ relays the needs of the demand-side model to the supply-side files. Moreover, it allows to cap the demand in the case when the chiller cannot meet the buildings requirements (exceeds its maximum capacity). For this we are using another **ExternalInterface:Actuator** that allows us to limit the maximum amount of mass flow rate that the **TemperatureSource** can supply.

2.1.3 Simulink Blocks

The MLE+ S-functions blocks need to be set to allow direct feedthrough. This could create algebraic loop in the simulation so there is the need to include delay blocks in the control signals from the Chiller to the buildings (Maximum mass flow rate and Inlet water temperature). Setting direct feedthrough ensures that during the same time step both buildings simulate (run through one EnergyPlus time step), produce their output and feed that to the Chiller block. The outputs of the buildings that are fed to the Chiller are the mass flow rate and the required power load at every time step. A single time step of the whole simulation ends when the Chiller block has executed and produce new outputs (Maximum mass flow rate and Inlet water temperature). Like we have connected EnergyPlus models to interact with each other, we can add other models using S-function blocks to add external models like C++ models or models in Matlab/Simulink.

2.2 Co-simulation Setup

In MLE+, data is exchanged between Matlab and EnergyPlus using a fixed synchronization time-step; determined by the EnergyPlus simulation time-step. There is no iteration between Matlab and EnergyPlus. In the co-simulation literature, this coupling scheme is referred to as quasi-dynamic coupling, loose coupling or ping-pong coupling Hensen (1999); Zhai and Chen (2005). Other data synchronizations may be possible. For example, in strong coupling, within each time step, both simulators exchange data until a convergence criteria is satisfied. This implementation requires the numerical solution of a nonlinear system of equations in which the termination criteria is a function of the state variables of the coupled simulators. However, many building simulation programs contain solvers that compute with relatively coarse precision. This can introduce significant numerical noise which may cause convergence problems for the co-simulation. Loose coupling required shorter synchronization time steps and the work per time step was smaller (as no iterations were needed) which caused loose coupling to compute faster than strong coupling. An additional implementation benefit of loose coupling is that state variables need not be reset to previous values. Thus, loose coupling is easier to implement, is numerically more robust and it computed faster Trcka et al. (2007).

2.2.1 Data Exchange

By using the **LoadProfile** and **TemperatureSource** objects, we ensure that the internal mass and energy balance is handles by EnergyPlus and MLE+ facilitates the exchange of variables at each time-step between the supply side and demand side. Each component maintains its own continuity of mass and energy as well as local convergence and stability. They will only exchange variable values at each time step Wetter (2011). At every time-step, The **LoadProfile** object is used to simulate a scheduled demand profile. This can be useful when the building loads are already known. Demanded load and flow rate are schedules specified in the object definition. The load profile can specify heating and cooling loads. Cooling loads are entered as negative numbers. The actual load met is dependent on the performance of the supply loop components. The **LoadProfile** object is connected on the demand side of the plant loop. If desired, multiple **LoadProfile** objects can be combined in series and/or parallel. The **LoadProfile** object calculates the outlet water temperature, T_{out}, based on the inlet water temperature from the plant loop, T_{in}, and MLE+ inputs for the demand side load, Q_{load} , and the requested flow rate, $\dot{m}$. The calculation can be expressed in the equation:

$$T_{out} = T_{in} - \frac{Q_{load}}{\dot{m}c_p} \quad (1)$$

The user requested flow rate is not always available from the supply side plant loop. The actual flow rate used in the calculation is the lesser of the user requested value and the plant available value. Note that the **LoadProfile** object can still request and receive flow even if the scheduled plant load is zero. In this case the outlet temperature will be the same as the inlet temperature. This allows MLE+ to drive the plant loop flow without necessarily affecting the loop temperature. The values of the determined mass flow rate and outlet temperature is then fed back to the demand side using the **TemperatureSource** object and this repeats at each time-step.

Case Study: Campus-wide Energy Simulation

In this section, we present a case study to describe how a campus is simulated with MLE+. The goal is to show how MLE+ can be used to model multiple buildings on the demand side connected to a common supply loop. The ability to simulate such a large and a complex systems aids the investigation of campus-wide supervisory control and demand response strategies.

We first present the description of the campus simulated using MLE+. Following that we present the results of implementing campus-wide control strategies for demand response. We showcase the use MLE+ to evaluate the performance multiple demand response strategies.

Table 1: Building Characteristics

Building	Ave. Power (kW)	HVAC	Area (m^2)	Occupants
Office 1	800	4 VAV	46,320	2,397
Hospital	600	2 VAV, 2 CAV	22,422	612
Office 2	800	4 VAV	46,320	2,397

2.3 Campus Simulation

The demand side of the campus consists of three buildings, two large offices and a hospital, each of which is modeled using EnergyPlus. The cooling demand is met by two centrifugal chillers, also simulated in EnergyPlus. Figure 2 shows the configuration of the chilled water loop and its connection with the campus buildings. The chillers and primary pumps make up the supply-side equipment, while the buildings cooling loads, fans and secondary pumps correspond to the demand-side. The co-simulation (and EnergyPlus) time-step was 120 seconds. This value was chosen based on the dynamics of the building loads and chiller plant response.

2.4 Demand-side Load Modeling

The characteristics of each building are summarized in Table 1. The two office buildings are similar to each other and have identical characteristics. Fig. 5 shows a comparison of different aspects of the load profile of the different building types for three days. The ambient temperature has also been plotted (in black) for reference and the hospital temperature is shown with the dashed line. The power consumption of the office building tends to exhibit more changes than the hospital's power consumption.

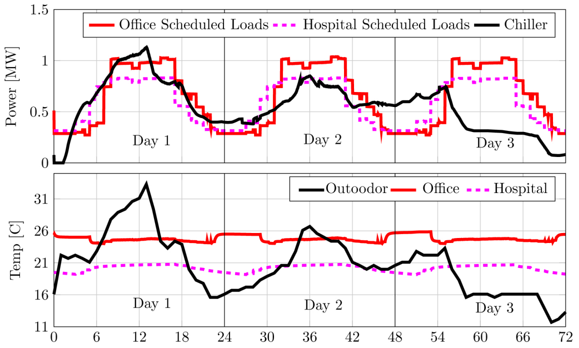


Figure 5: Comparison of the power consumption and thermal comfort of the buildings and the chiller.

This is because, although they are subject to the same outdoor conditions, the occupancy of the office building changes during the day which causes the corresponding change in the power consumption profile of the building.

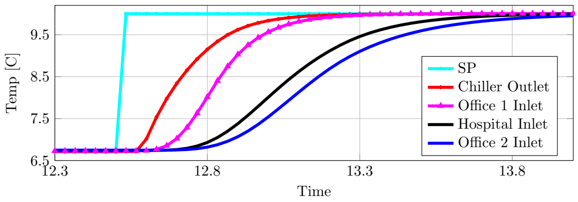


Figure 6: Piping delay (in hourly time) due to Chilled-Water setpoint change

Furthermore, the hospital has much stringent thermal comfort requirements than the office buildings. Due to the constant need to conditioning the emergency rooms and other sensitive areas of the hospital, its power consumption is uniform and higher throughout the day.

Since the buildings are physically located at different distances from the chiller plant so their chilled water temperature which they receive is different for each of them. This is also modeled using EnergyPlus. The effect of the varying piping length can be seen in Fig. 6. It can be seen how the chilled water temperature changes after a delay based on its distance from the chiller. For example, at 12:48pm the supply water inlet temperature at the first office is already 8 °C while at the second office is still 6.8 °C.

2.5 Supply-side Chiller Modeling

The chiller plant consists of two centrifugal chillers, connected in parallel, with a total rated capacity of 1.1MW. The chillers are modeled using the `Chiller:Electric` object in EnergyPlus. This object uses performance curves for cooling capacity and efficiency to determine the chiller operation for different reference conditions.

Evaluating Demand Response Strategies

Demand response may be triggered due to economic reasons when the price of electricity increases rapidly due to increased grid load or due to emergency reasons to ensure reliable grid operation. In economic DR, participants receive a financial incentive for curtailing during their load during system/grid level contingencies. The demand response happens as an event, i.e. the utility signals the consumer to respond and curtail their load in a particular way which can vary based on the specific program. However, almost always there is a notification sent by the utility prior to the beginning of the curtailment period. This notice to curtail can vary from 30 minutes to a few hours. The notification is followed by the start of the actual curtailment period, the duration of which is also determined by the utility and the type of DR program. An example of such a scenario is shown in Figure 7.

[b]

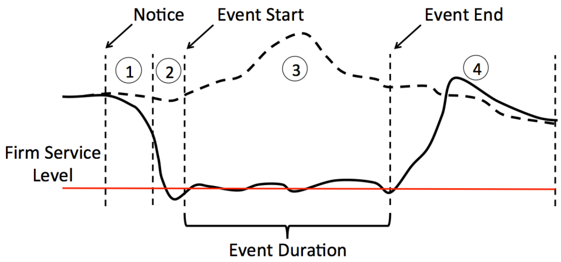


Figure 7: Stages for Coordinated DR

As an example, in the PG&E's Base Interruptible Program (BIP) the end-user receives a 30-minute advance notification about the curtailment event. In this program, the consumer must curtail at least 15%of their average monthly load or a minimum of 100kW, whichever is greater. The participant receives $\$8-9/kW$ of energy curtailed. However, failure to reduce load down to below a reference (or promised) value, also known as the Firm Service Level (FSL), can result in a penalty of up to $\$6/kWh$.

At the campus-level, the execution of DR strategies are largely ad-hoc and based on a set of pre-determined rules. When an event is anticipated, the customer can respond by switching off equipment and by adjusting set-points across the system. Such naive strategies do not take into account the dynamical behavior of the supply and the demand sides. This is mainly because the large and complex system at a campus-scale cannot be easily analyzed in detail for the prevailing conditions. MLE+'s ability for simulating large systems presents an opportunity to evaluate DR strategies which take into account the interactions across the entire campus.

Table 2: Comparison of Supervisory Control Based Demand Response

Strategy	Response Time	Curtailment	Kickback	Disconfort
Chiller Set-Point	Fast	High	High	Moderate
Supply Air Temperature	Fast	Moderate	Low	High
Room Set-Point	Slow	Moderate	High	High

2.6 Supervisory Control Based Demand Response

The dynamics of the campus, power consumption, response time for changes to take effect, can be affected by changing set-points at different levels in the system. Three supervisory control based demand response strategies are evaluated:

1. Chilled-Water Supply Temperature.
2. Supply Air Temperature.
3. Room Temperature Set-point.

We simulate the campus operation for a hot day (June 8^{th}). The simulation step is 2 min. However, the supervisory setpoint control is only allowed to change on 10-minute intervals. The DR event starts shortly after noon, has a 30 minutes advance notification time, and a duration of 2 hours.

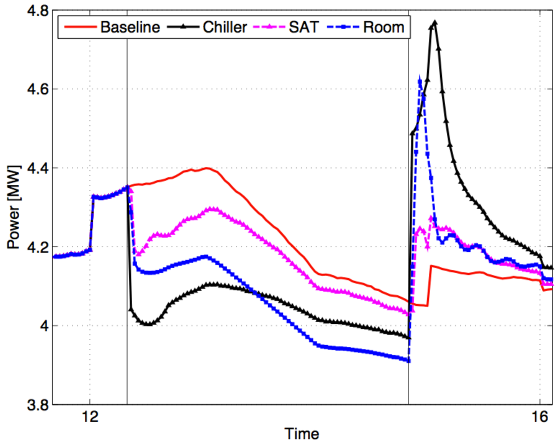


Figure 8: Step Demand and Supply Strategies.

1. **Chilled-Water Setpoint Increase:** This method slows down the centrifugal compressor directly decreasing its power consumption. However, this may increase the pump and fan power consumption due to the higher chilled-water temperature which might not be enough to provide the necessary cooling for maintaining comfort. Changing the supply-water setpoint provides a faster change in the power consumption as we are directly affecting the largest fraction of the total power consumption through the chiller. At the end of the DR event, the supply water setpoint is returned back to its default value. This peak can lead to large demand charges that appear in the capacity part of the electric bill.
2. **Supply-Air Temperature (SAT) Setpoint Increase:** This is a curtailment on the building side that can quickly reduce the fan power consumption. This decrease in the power consumption due to the immediate decrease in the fan speed. Although the response time between changing the SAT and observing the decrease in the power consumption is small, the magnitude of the power reduction itself is limited, mainly because the fan power does not account for a large power reduction.
3. **Room Setpoint Increase:** Increasing the room temperature setpoint directly affects the cooling demand. The room temperature setpoint increase exhibits the fly-wheel effect, the thermal inertia of the room creates a delay in the reduction of power consumption of the fan and with enough time the curtailment eventually propagates to the chiller side reducing its power consumption. This response time with this strategy is much longer that previous two strategies due to the capacity of the rooms, the air-loop and the chilled water loop. Moreover, increasing the room setpoint directly affects the thermal comfort experienced by the occupants and can lead to discomfort.

Fig. 8 presents the effect in power consumption of three curtailment strategies triggered individually. Table 3 shows characteristics of the following step DR strategies.

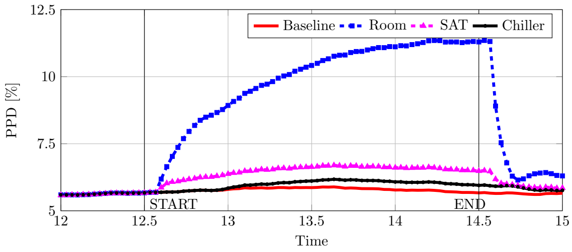


Figure 9: Percentage of Dissatisfied People (PPD).

[b]

Table 3: Step Demand & Supply Strategy Characteristics

Strategy	Reduction [kW] (%)	Kickback [kW] (%)	Delay[min]
Room	388(4.53%)	561(13.84%)	20
Supply-Air	151(1.76%)	182(4.49%)	2
Chilled-Water	499(5.82%)	560(13.81%)	12

The delay in Table 3 is calculated as the time between the change in the set point and the observed maximum curtailment in the power consumption. The reference value for the curtailment is the baseline consumption with no DR strategy. In reality, the baseline could be estimated based on trends of historical consumption data. Fig. 9 shows the plot of the Percentage of People Dissatisfied (PPD). This is a standard measure to quantify thermal comfort. Finally, Fig. 10 presents the average room temperature for the office zones.

2.7 Coordinated Demand Response

As shown, each of the three supervisory control based curtailment strategies have their merits and limitations. Based on their response characteristics, a smarter demand response strategy should consider coordinating the three simpler demand response schemes to reduce occupant's discomfort, reduce kickback effect and maximize the power reduction during the DR event.

To formulate a strategy, we consider the time interval from the notification of the DR event to its conclusion.

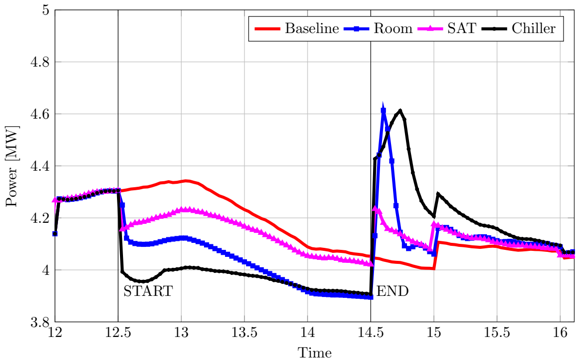


Figure 10: Average Room Temperature per Building.

This time interval can be divided into the four different stages as follows

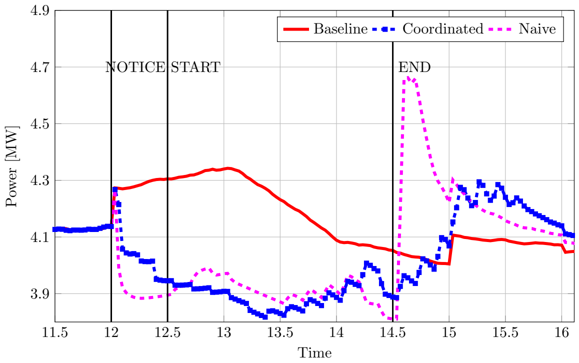


Figure 11: Coordinated vs. Naive.

1. **First Pre-event** This includes the curtailment strategies on the building side. The setpoints for the room and supply air temperature are increased so as to allow for enough time for its effect to propagate to the chiller side.
2. **Second Pre-event** This includes a mix of setpoint adjustments on both the chiller side and the buildings. The chilled-water setpoint is increased just prior to the event since the response time to observe the corresponding reduction in power is short.
3. **During:** During the event, all three setpoints are simultaneously adjusted. However, only small changes are preferred to achieve the desired curtailment level.
4. **Recovery:** In recovery stage as the setpoints are gradually reset. The recovery hast to be gradual in order to avoid a large kickback.

Figure 7 shows the different time intervals for a power consumption profile achieved due to a coordinated DR strategy. The intervals have been labeled according to the strategy described above.

Figure 11 compares a coordinated DR strategy with the supervisory control approach. The coordinated DR approach carefully balances individual setpoint strategies based on thier response time and expected power reduction. Also, the coordinated approach gradually lowers the setpoints during the recovery interval to reduce the kickback effect. Table 4 presents the comparison of results of both curtailment approaches.

Table 4: Coordinated vs. Naive DR

DR Strategy	**Curtailment (kW)**	**Kickback (kW)**
Coordinated	323(7.55%)	242(6%)
Naive	306(7.15%)	610(15%)

Related

Building simulation tools like EnergyPlus Crawley et al. (2000), TRNSYS Klein and Solar Energy Laboratory (1976), ESP-r Strachan (2000), eQuest, DOE-2 Winkelmann et al. (1993) and DesignBuilder Tindale (2005) offer powerful methods for simulating realistic behavior of buildings and for evaluating their energy efficiency and sustainability. However, their use for simulating large systems like a campus has been an area of limited research.

Although, we propose and implement demand response schemes for the whole campus, the focus of this paper is not to propose novel strategies for demand response but to utilize the MLE+ approach for enabling such large scale, high fidelity simulations with EnergyPlus. Motegi et al. (2007) presents a thorough treatment of demand response strategies for commercial buildings.

2.8 Comparison with BCVTB

Building Control Virtual Test Bed (BCVTB) is a software environment for coupling different simulation programs. It can interface different simulation programs for co-simulation, including EnergyPlus and Matlab. The co-simulation feature in EnergyPlus was originally developed for BCVTB and can be used by any program to perform co-simulation with EnergyPlus. MLE+ is an example of such a program.

Full Matlab capabilities are hindered when coupled EnergyPlus via BCVTB, this occurs as Matlab is only called by BCVTB as an executable client. Therefore, interactive execution and debugging of Matlab code is not possible. Furthermore, if the Matlab code or the Simulink model has an error, it is much more difficult to find and fix it with BCVTB than with MLE+, which runs in the standard Matlab environment. For users who mostly work with Matlab/Simulink and have never used Ptolemy, learning a new environment as Ptolemy is time-consuming. For further details on the advantages of MLE+ over BCVTB and better discussion can be found in REF.

Conclusion

Using the open source and free toolbox MLE+, we have extended the capability of EnergyPlus to simulate a large campus in a modular manner. This is done by utilizing MLE+'s Simulink block which allows for co-simulation between different EnergyPlus models(files) which share common resources. We can successfully simulate a campus comprising of multiple buildings on the demand side and a common chilled water resource, like a central chiller plant on the supply side. The capability of running a large scale campus wide co-simulation using EnergyPlus is quite novel. It opens up the possibility of utilizing such simulations for determining optimum operational conditions for such systems, containing several subsystems with coupled dynamics. Using the virtual campus as a test-bed we also evaluate several demand response strategies at a campus level and characterize their performance. In addition, we propose and evaluate the performance of a coordinated supervisory demand response strategy which can curtail during a DR event while minimizing the adverse effects of curtailment such as discomfort and kickbacks. We are also working towards utilizing cloud based services to help speed up simulations of this scale.

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