Conceptual Framework for a Multi-building Peak Load Management System

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***Abstract*—A building energy management (BEM) system serves as the key element of a smart building. It facilitates grid interaction and participation of a building in a demand response (DR) program. Typically, a BEM has been designed to manage loads in a single building. However, in reality, a number of adjacently located buildings can be owned by a single entity, like a campus. In this case, during DR events, instead of optimized control of loads in a single building, the coordinated control of loads in multiple buildings should be conducted to ensure the best operation condition for the entire facility. This paper proposes a conceptual framework to coordinate the operation of loads in multiple buildings, thereby reducing the peak demand of the entire facility during a DR event while minimizing occupant discomfort. Simulation results indicate that the proposed framework for coordinated control of multiple buildings results in less occupant discomfort than controlling loads in each building individually.**

***Index Terms*—multi-building, demand response, peak load management, smart building**

I. INTRODUCTION

Buildings consume over 40% of the total energy consumption in the U.S. and over 70% of the nation's total electricity usage today [1]. Authors in [2] points out that a large amount of energy consumed in buildings is wasted due to lack of automatic control systems. Building energy management (BEM) systems can enable autonomous and intelligent control of modern commercial buildings to improve occupant comfort, increase energy efficiency and save utility bills. An increasing number of large commercial buildings have installed such a system to control their major loads. According to [3] and [4], controlling lighting and HVAC systems can achieve electricity savings of 40% and 20%, respectively, and deploying a building automation system can allows a building to spend 8%-20% less on operational costs[5] .

Research on BEM improvement to better provide energy savings in a single building has been studied extensively. For example, a load scheduling scheme for BEM has been studied in [6] to make buildings demand responsive. A framework for multi-agent decision making process is proposed to improve building energy efficiency in [7]. Hardware designs for energy management systems to be responsive to electricity real time price have been demonstrated in [8] and [9]. Optimized control of HVAC, lighting and shading systems is studied in [10] while taking into account of the electricity price.

In case of multiple buildings, it is also common that they belong to a single entity, such as a military base or a university campus. In such cases, a coordinated control of loads in multiple buildings will ensure the optimal operation for the entire facility. Currently, literature on collaborative management of loads in multiple buildings is very limited. Though authors in [11] discussed HVAC control by limiting the maximum number of RTU units in operation at each time slot, setting such an upper limit is subjective when dealing with a facility that has a number buildings. Therefore, to address the knowledge gap, this paper proposes a conceptual framework for a multi-building peak load management system, which is designed to manage peak load of a campus-type facility during a demand response (DR) event. The proposed framework targets small and medium sized commercial buildings which are owned by a single entity.

II. FRAMEWORK OF THE PROPOSED MULTI-BUILDING PEAK LOAD MANAGEMENT SYSTEM

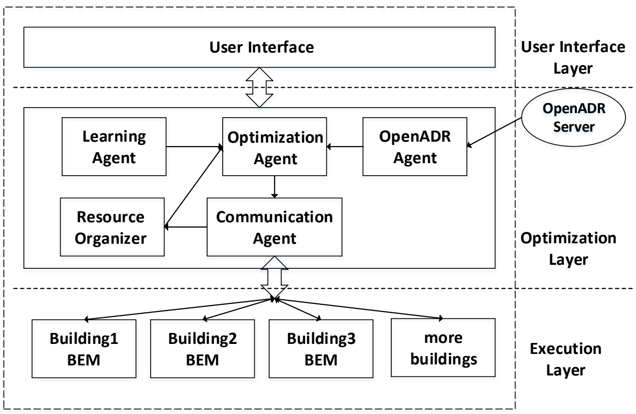

Fig. 1. Architecture of the multi-building peak load management system.

Fig. 1 depicts the architecture of the proposed multi-building peak load management system, which comprises

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three layers: the user interface layer, the optimization layer and the execution layer. Each layer is explained below.

A. User Interface Layer

The user interface layer hosts the user interface of the proposed framework. With authentication, the facility manager can log in and retrieve real-time energy consumption data of different buildings and edit control configurations.

B. Optimization Layer

Five agents resided in the optimization layer are discussed below.

1) OpenADR agent: This agent receives DR signals from an OpenADR server and triggers the optimization agent to initiate the optimization process.

2) Learning agent: A optional learning agent is responsible for learning HVAC behavior and selecting optimization coefficients of each building.

3) Communication agent: This agent receives load profile information (e.g., power consumption) from different buildings, and forwards the information to the resource organizer agent. Once an optimized control decision is made, the communication agent sends these control signals to different buildings.

4) Resource organizer agent: This agent receives information from the communication agent, generates a summary table of all controllable loads from different buildings, and updates the table with information from the optimization agent at selected time intervals.

5) Optimization agent: When receiving a signal from the OpenADR agent, the optimization agent is activated and starts its optimization process based on the latest controllable load table obtained from resource organizer agent. After completing its decision making process, the optimization agent dispatches control signals to each building via the communication agent.

C. Execution Layer

The execution layer consists of multiple BEM units associated with each building in the campus-type facility. The building energy management open source software (BEMOSS™) platform [12] that has been developed by Virginia Tech, USA, is an example of an open-source BEM system that can be used in the execution layer to enable a cost-effective energy management in buildings. To collaborate with the optimization layer, BEM periodically reports the building's load profile to the communication agent in the optimization layer and performs load control according to the signal received from the communication agent. In the reported load profile, two main categories of controllable loads, i.e., HVAC and interruptible loads (IL) are included. See Table I.

D. Peak Load Management Procedure

Fig. 2 depicts how this proposed system works before a DR event starts and during a DR event. Note that a facility manager/owner will have a list of buildings to be participated in a DR event. Non-participating buildings will not be controlled. The list of participating buildings can be updated anytime which makes the system flexible to changes.

Before a DR event starts, a BEM unit in each participating building send its building load profile to the optimization layer via communication agent. Building load profile includes the amount of HVAC, interruptible loads (kW) and temperature readings in each thermal zone of a building. These information then passes to the resource organizer, which collects the most recent load information of all buildings.

During a DR event, BEM in each participating building first sheds Level-I IL. If more loads need to be shed, the optimization agent will start its process to determine the best coordinate control strategy among loads of different buildings. Eventually, this strategy will be sent to all BEM units, each of which then executes a specific load control strategy.

TABLE I. LOAD CATEGORY AND CHARACTERS

	Load Category	**Sub-category / Characters**
Two main categories of controllable loads	*HVAC*	ON/OFF status of HVAC compressors will be controlled by changing thermostat set points. This directly influences occupant comfort.
	Interruptible Loads (IL)	Level-I IL: IL that causes no discomfort to building occupants regardless of its OFF duration. This type of load will be shed first and will not be part of optimization. Examples are decorative lightings.
		Level-II IL: IL that can cause occupant discomfort after being shed, depending on the cut amount and duration. Examples include workspace lighting, printers and copy machines.

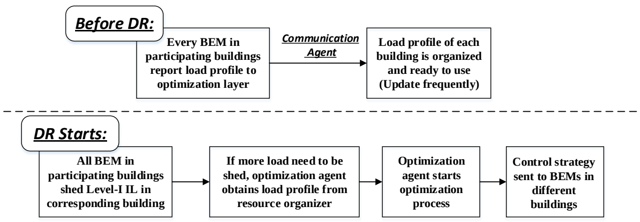

Fig. 2. Flow chart for system operation.

III. OPTIMIZATION MODEL

The goal of the optimization agent is to help buildings achieve the DR load shedding goal while minimizing overall occupant discomfort. The optimization model, which is embedded in the optimization agent, is discussed below. According to [13-15], the winter power system peak load is around 20% lower than the summer peak load. In this case, demand response will be more prevalent in summer than winter. As a result, in this section the optimization model is designed for summer cases, where HVAC is running on cooling mode. Minor changes can be applied to adapt to winter cases.

A. Decision Variables

Decision variables in this model are S_t^h and X_t^k. S_t^h are Boolean variables representing operating status of HVAC unit h (ON/OFF) at time t. X_t^k are continuous variables that represent the amount of interruptible load (kW) remaining in building k at time t.

B. Objective Function

The objective function is to minimize overall occupant discomfort throughout a DR event. The occupant discomfort is defined as (1):

$$\min: D=\sum_{k=1}^{K}\sum_{t=1}^{T}D_{IL}(X_t^k,X_{t-1}^k,P_{IL}^k)+\sum_{h=1}^{H}\sum_{t=1}^{T}D_{HVAC}(Temp_t^h) \quad (1)$$

The occupant discomfort (D) is determined taking into account the thermal discomfort (D_{HVAC}) and inconvenience caused by shedding interruptible loads (D_{IL}). In (1), K and H represents the total number of buildings and HVAC units, respectively. T represents the total number of time slots during a DR event.

The thermal discomfort (D_{HVAC}) is caused by the increase in indoor temperature outside a desirable range $[T_{min}^h, T_{max}^h]$. The thermostat set point of each HVAC unit will be adjusted to maintain the indoor temperature of each zone to always be above T_{min}^h. When the indoor temperature is within the desirable range, it is assumed that occupants feel comfortable and hence the thermal discomfort index is zero. When the indoor temperature is above T_{max}^h, occupant discomfort will occur. This paper assumes that the occupant discomfort has a linear relationship with the deviation of indoor temperature from T_{max}^h. Thus, D_{HVAC} can be written as (2):

$$D_{HVAC}(Temp_t^h)=\begin{cases}0 & \text{if } Temp_t^h\le T_{max}^h\\ \alpha_t^h(Temp_t^h-T_{max}^h) & \text{if } Temp_t^h>T_{max}^h\end{cases} \quad (2)$$

α_t^h in (2) is the thermal comfort priority coefficient of the thermal zone of HVAC unit h in time slot t, which is a parameter that the facility manager or the learning agent will set.

Shedding interruptible loads in buildings might make some appliances unavailable to occupants and the more the IL shedding, the more the building occupants feel inconvenient. Moreover, occupants also feel discomfort at the moment when their devices being turned off. Therefore, D_{IL} at time t can be written as (3).

$$\begin{aligned}&D_{IL}(X_t^k,X_{t-1}^k,P_{IL}^k)\\&=\begin{cases}\varepsilon_t^k(P_{IL}^k-X_t^k) & \text{if } X_{t-1}^k\le X_t^k\\ \varepsilon_t^k(P_{IL}^k-X_t^k)+\delta_t^k(X_{t-1}^k-X_t^k) & \text{if } X_{t-1}^k>X_t^k\end{cases}\end{aligned} \quad (3)$$

ε_t^k and δ_t^k in (3) are the load insufficiency discomfort coefficient and the load shedding discomfort coefficient of building k in time slot t, which also can be set by the facility manager or the learning agent.

C. Constraints

- At any time, the IL consumption in any building during a DR event should be lower than its original amount:

$$0\le X_t^k\le P_{IL}^k \quad (\forall k,\forall t) \quad (4)$$

- At any time the total power consumption of these buildings should below the DR limit:

$$P_t^{total}=\sum_{k=1}^{K}X_t^k+\sum_{h=1}^{H}S_t^h\cdot P_{Normal}^h+P^{base}\le P_t^{DR} \quad (\forall t) \quad (5)$$

P_t^{DR} is the DR limit at time t, P_{Normal}^h is the rating of compressor h and P^{base} is the amount of base load.

- Indoor air temperature in any building should be above their minimum allowed value:

$$Temp_t^h\ge T_{min}^h \quad (\forall h,\forall t) \quad (6)$$

- According to [16], indoor air temperature can be calculated by (7):

$$\begin{aligned}&Temp_t^h=f(Temp_{t-1}^h,S_{t-1}^h)\\&=Temp_{t-1}^h+\Delta t\cdot\frac{G^h}{\Delta c^h}+\Delta t\cdot\frac{C_{HVAC}^h}{\Delta c^h}\cdot S_{t-1}^h \quad (\forall h,\forall t>1)\end{aligned} \quad (7)$$

Δt is the length of each time slot (hr), G^h is the heat gain rate of thermal zone under compressor h (Btu/hr), Δc^h is the energy needed to change the indoor temperature by 1 degree (Btu/degree) and C_{HVAC}^h is the cooling capacity of compressor h (Btu/hr).

With G^h written explicitly, (7) can be reorganized as (8).

$$\begin{aligned}&Temp_t^h=(1-\frac{A}{R}\cdot\frac{\Delta t}{\Delta c^h})Temp_{t-1}^h+(\frac{A}{R}\cdot Temp_{t-1}^{out}+\\&solar^h)\cdot\frac{\Delta t}{\Delta c^h}+\Delta t\cdot\frac{C_{HVAC}^h}{\Delta c^h}\cdot S_{t-1}^h \quad (\forall k,\forall t>1)\end{aligned} \quad (8)$$

A/R is the ratio of area of wall, ceiling and window to their heat resistance, and $solar^h$ describes heating effect by considering solar radiation through windows[16]. However, if buildings' parameters are unavailable, an algorithm can be embedded in a learning agent, allowing the agent to characterize indoor temperature profiles based on experimental data. This is not in the scope of this paper and will not discuss here.

IV. CASE STUDY

This section evaluates the proposed multi-building peak load management algorithm using simulation studies. Simulations are conducted using MATLAB and IBM CPLEX, which run on a PC with 8GB RAM and Intel i5 CPU.

A. Input Assumptions

TABLE II. BASIC BUILDING INFORMATION

Building No.	**1**	**2**	**3**
Area (sq. ft.)	9018	6966	4447
No. of thermal zones	6	4	3
Total HVAC load (kW)	21	15	11
Total IL load (kW)	19	12	8
Total base load (kW)	30	23	16
Peak Load (kW)	67	50	35

To simplify the problem and without loss of generality, a campus with three small and medium sized buildings are studied. Its basic information is summarized in table II.

The number of thermal zone is determined by the building size. Each thermal zone in buildings corresponds to a HVAC unit, and the unit sizing is calculated according to ASHRAE standard [17]. HVAC loads account for 30% of the total load in buildings. Total IL load, base load and building peak load are given with reference to [18]. Typical values are used for other building parameters, such as G^h and A/R. Weather information is acquired from the National Climatic Data Center (NCDC) [19].

Without DR, during a one-hour afternoon in the month of August, load profiles of three buildings are simulated in MATLAB and depicted in Fig. 3. It is assumed that all IL loads in three buildings are in operation and HVAC units operate to maintain the indoor temperature of each building within their desirable ranges $[T^h_{min}, T^h_{max}]$. As Fig. 3 shows, without peak load management, the total power consumption of three buildings reaches 152 kW at the 7th minute.

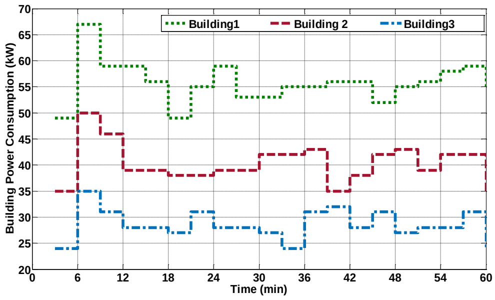

Fig. 3. Buildings load curve (1 hour) without DR.

To demonstrate the effectiveness of the proposed multi-building peak load management algorithm, the simulation of a 1-hour DR event at 3-minute time resolution ($\Delta t = 1/20$) is conducted. This paper compares the case of multi-building coordinated optimization and individual building optimization, both using the same optimization algorithm proposed in Section III.

For the multi-building coordinated control, the total demand limit is set for the entire facility (which has three buildings in this case). For the individual building control, each building receives its own demand limit from the utility, which can be evaluated based on a walk-through survey and building historical power consumption data. The following demand limits are used in the simulation study.

- Individual control: $P_{b1} = 40kW$, $P_{b2} = 30kW$, $P_{b3} = 25kW$
- Coordinated control: $P_{b123} = P_{b1} + P_{b2} + P_{b3} = 95kW$

Parameters to calculate occupant discomfort index are set the same for all buildings as $\alpha = 10$, $\varepsilon = 0.5$ and $\delta = 1$. In reality, facility managers can choose different values for these parameters to prioritize different buildings.

B. Results and Discussions

Table III compares the resulting discomfort indices between individual building control and coordinated control of three buildings. In both situations, the total demand limit is 95 kW for three buildings. $D_i(P_{bi})$ denotes the minimized occupants discomfort index of building *i* calculated using the proposed algorithm in Section III, when building i has the demand limit of P_{bi}. The result is the global minimum of all the buildings participated, it indicates that coordinated control of three buildings results in less occupant discomfort than when controlling these buildings individually.

TABLE III. DISCOMFORT COMPARISON BETWEEN INDIVIDUAL CONTROL AND COORDINATED CONTROL

Individual control of three buildings		Coordinated control of three buildings	
Demand limit	Discomfort Index	Demand limit	Discomfort index
P_{b1} = 40 kW P_{b2} = 30 kW P_{b3} = 25 kW	D_1(40)+ D_2(30)+ D_3(25) = 357.94	P_{b123} = 95 kW	$D_{123}(95) = 334.28$

In fact, the decrease in occupant discomfort is because the proposed coordinated control system allows all buildings to fully utilize the allowable demand limit. According to Fig. 4, when all three buildings are controlled collectively, the facility load curve is almost always kept at the specified demand limit of 95 kW.

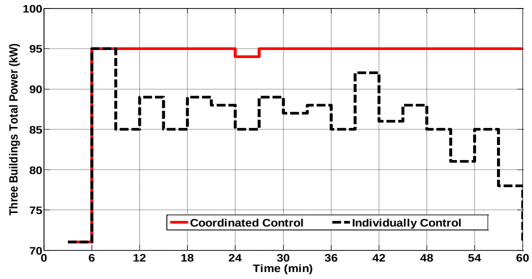

Fig. 4. Facility load curve (1 hour) using the proposed multi-building peak load management algorithm vs control of individual buildings

On the other hand, when controlling each building individually, there is the lack of coordination, hence the aggregated building load curve is always below the specified demand limit. This is considered capacity 'wasted', and thus resulting in more occupant discomfort.

When taking a closer look into each building's load curve in Fig. 5, it can be seen that each building can adjust its power consumption according to other buildings' needs, thus fully utilizing the specified demand limit.

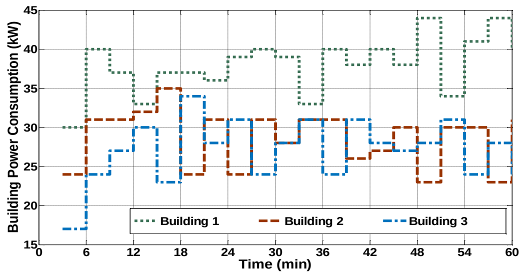

Fig. 5. Building load curves (1 hour) with coordinated control.

C. Evaluation of Algorithm Efficiency

TABLE IV summarizes the efficiency of the proposed optimization algorithm. GAP in TABLE IV represents the difference between the current objective function value and the optimal solution. Showing together with GAP is the solution convergent time, which is the time required for the optimal solution to be obtained at the specified GAP. Nv is the number of decision variables in the optimization problem.

TABLE IV. OPTIMIZATION EFFICIENCY

P^{DR} **(kW)**	**Buildings 1+2+3 (Nv=320)**	
95	GAP=1%	GAP=2%
	101.94 sec	14.01 sec
100	GAP=1%	GAP=2%
	79.64 sec	15.58 sec
105	GAP=1%	GAP=2%
	69.50 sec	16.34 sec

When adopting 2% GAP, the three building optimization problem can be solved within 15 seconds. Since a DR event is typically announced several hours in advance, the proposed algorithm is proven to be efficient and able to manage peak demand in real time. However, it is worth noting that when a large facility with 100+ buildings is considered, the efficiency of the proposed algorithm needs to be further evaluated. This is to be conducted as the future work.

V. CONCLUSION

This paper has proposed framework to conduct coordinated multi-building peak load management. System architecture and control procedure are presented. In addition, the optimization model used by the optimization agent is proposed and tested. Simulation results demonstrate that by adopting the proposed multi-building control system, overall occupant discomfort can be minimized globally. The proposed structure is deemed to be flexible and scalable and will remain robust when the number of buildings changes. Other advantage of using the proposed approach is its ability to control demand restrike after a DR event is over, this can be done by raising P_t^{DR} gradually. Overall, the proposed approach demonstrates its superior ability to manage the entire facility peak load by a control of multiple buildings coordinately as opposed to controlling each building individually.

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