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# Optimal power demand management for cluster-level commercial buildings using the game theoretic method

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**Abstract**

Power demand management, particularly demand response controls, is the effort from the demand side to help the supply side management for helping maintain grid balance and also bring the economic benefits for building owners. Most of building demand management and demand response control strategies for commercial buildings only focus on a single building. However, as for the cluster-level buildings, which are sometimes involved in an account for electricity charge and also the main concern of smart grids, such conventional individual-level control strategies will not be effective. A game theory-based decentralized control strategy is therefore developed for cluster-level building demand management by simultaneously optimizing the indoor air temperature set-point and the operation of active thermal storage. Without gathering all the required information of buildings to a central optimization system, the cluster-level building demand management can be realized in a decentralized way. Case studies are conducted and results show that the proposed decentralized control strategy can increase the peak demand reduction, over two times than that when the demand management of buildings is conducted in an uncoordinated mode. Meanwhile, the performance of the proposed decentralized control strategy is closely approached to the results that are optimized in a centralized mode.



*Keywords:* game theory; building demand response; cluster-level building; thermal storage; peak demand; smart grid

## 1. Introduction

The energy consumption of buildings has grown rapidly in recent years due to the increasing population, the rising demand for healthy and comfortable indoor environments, the global climate changes, etc. Approximately 40% of

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global energy is consumed by buildings [1]. In the United States, buildings accounted for 74% of electricity use in 2010 [2], while even more in Hong Kong, 91% of total electric energy was consumed by buildings in 2009 [3]. In addition to the challenge from energy-intensive buildings, peak load is another serious issue. Huge investment in upgrading the power grids is needed to meet the peak load of a power grid. Due to these two critical issues, the monthly electricity bills for buildings in some regions, such as Hong Kong, are always based on the monthly energy consumption and monthly electrical peak demand. The payment for monthly peak demand in a commercial building always constitutes a great part of the electricity bill [4].

Central air-conditioning systems account for a large part of energy use of commercial buildings, particularly in subtropics climate. Meanwhile, due to their elastic nature of power use and the help of advanced technologies such as building automation systems and smart meters, building power demand management contributed by central air-conditioning systems could be very promising. Many studies have been conducted for building demand management contributed by central air-conditioning systems [5,6]. But these methods always focus on a single-building rather than cluster-level buildings (i.e., more than one building). In addition, no study has been conducted for cluster-level building demand management and simultaneously optimize the operation of both active and passive thermal storages. This study, therefore, develops a game theoretic method to optimize the cluster-level building power demands by optimizing their individual indoor air temperature set-points and charging/discharging processes of the active thermal storage. Instead of a central control system, i.e., every required measurement and system parameter are collected together for optimization, the proposed method can be implemented in a decentralized mode that buildings can optimize their own power demands separately to achieve the optimal cluster-level building demand management without the need to share their own information to a virtual central control system.

## 2. Problem illustration for cluster-level building demand management

Because the peak demand cost of a commercial building always constitutes a great percentage to the electricity bill, effectively reducing the peak demand in commercial buildings will bring significant economic benefits to building owners and also relieve the imbalance operation problem of power grids. However, most studies on building peak demand limiting only take a single building into account (i.e., individual-level method) rather than cluster-level buildings. When more than one building is involved in an account and hence their aggregated power demand is charged by utility companies, the performance of these individual-level peak demand limiting methods would be obviously relieved and even failure. The occurrence times of individual building peak demands are always different with that of their aggregated peak demand. As a result, using individual-level methods, the peak demand limiting conducted by some of the buildings may be no contribution to reduce their aggregated peak demand and even lead to appear a new peak of power use.

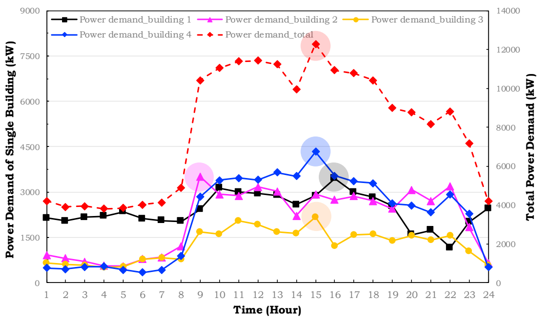


Fig.1 Power demands of individual buildings and their aggregated demand on the test day

The on-site data of building electricity on a Hong Kong university campus were selected to illustrate the above problem. Four buildings with central air-conditioning systems were involved in one account and charged by the utility companies. The data on July 3, 2017 (Monday) were collected from power meters and presented in Fig.1. These data were the power demands of central air-conditioning systems in buildings. The peaks of buildings and the account (i.e., the aggregated demand of four buildings) were highlighted in the figure. Obviously, the peak demand occurrence times of buildings and the account on the test day were inconsistent. If the peak demand limiting was conducted separately for buildings, the effectiveness of limiting controls in building 1 and building 2 would not benefit the peak demand reduction of the account. This was because the peak demands of building 1 and building 2 occurred at 16:00 pm and 9:00 am respectively, but that of the account occurred at 15:00 pm. Therefore, the building demand management should be conducted from the viewpoint of the cluster-level rather than the individual-level.

## 3. Proposed control strategy for cluster-level building demand management

### *3.1. Problem formulation*

The objective of cluster-level building demand management is to minimize their total electricity bill (the building associated to the account). The calculation of the electricity bill for the aggregated building power demand is shown in Eq.(1). Where, $C$ is the daily electricity bill of the account, $HKD$. $\alpha, \beta$ are the unit prices for electrical peak demand and total energy consumption, respectively. $PD_{tot}$ is the daily peak demand of the account, $kW$. $E_{tot}^k$ is the total energy consumption of the account at $k$ time slot (calculated by Eq.(2)), $kWh$. $N$ is the total number of equal size time slots in a day. $P_i^k$ is the power demand of building $i$ at $k$ time slot.

$$C = \alpha \times PD_{tot} + \sum_{k=1}^{N}(\beta^k \times E_{tot}^k) \tag{1}$$

$$E_{tot}^k = \sum_{i \in \delta} P_i^k \times t \tag{2}$$

The flexibility of power demand in each building is contributed by its central air-conditioning system in this study and the other parts of power demands are assumed to be the same as the original power profiles. The power demand of central air-conditioning system is mainly determined by the cooling demand in a building. The detailed calculation is shown in Eqs.(3-5). Where, $P_{tot}^k$ and $P_i^k$ are the power demands of the account (i.e., total demand) and building $i$ at $k$ time slot, respectively. $P_{i,ac}^k$ is the power demand of central air-conditioning system in building $i$. $P_{i,other}^k$ is the building power demand except the part of its air-conditioning system, which is set to be the same with the baseline and not contributed for building demand management. $cop_s$ is the coefficient of performance of the central air-conditioning system.

$$P_{tot}^k = \sum_{i, i \in \delta} P_i^k \tag{3}$$

$$P_i^k = P_{i,ac}^k + P_{i,other}^k \tag{4}$$

$$P_{i,ac}^k = Q_{i,dem}^k / cop_s \tag{5}$$

Every building associated to the account is equipped with an active thermal storage in its central air-conditioning system in this study. Meanwhile, building thermal mass is used as a passive thermal storage in each building to increase the flexibility of building power demand. The cooling demand of a building ($Q_{i,dem}^k$) is calculated based on Eq.(6). Where, $Q_{i,base}^k$ is the original cooling demand of building $i$. $\Delta Q_{i,active}^k$ and $\Delta Q_{i,passive}^k$ are building cooling demand alternations caused by the active and passive thermal storages at $k$ time slot, respectively. The cooling alternation caused by the building thermal mass is calculated by a simplified RC model, as shown in Eq.(7). The detailed of this RC model is shown in ref.(7). The cooling alternation caused by the active thermal storage is calculated by Eq.(8). Where , $T_{i,w,out}^k$ and $T_{i,w,in}^k$ are the chilled water temperatures at the outlet and inlet of the active thermal storage in building $i$ at $k$ time slot. $u_i^k$ is the control signal of the active storage for cooling charging/discharging at $k$ time slot. $M_{i,w,max}$ is the maximum chilled water flow rate though the storage. $\varphi$ is the cooling loss coefficient. $Q_{i,stored}^k$ is the total cooling stored in the storage at $k$ time slot.

$$Q_{i,dem}^k = Q_{i,base}^k - \Delta Q_{i,active}^k - \Delta Q_{i,passive}^k \tag{6}$$

$$\Delta Q_{i,passive}^{k} = \frac{T_{i,opt}^{k} - T_{i,base}^{k}}{R_{i,bui,out} + R_{i,bui,in}} \times \left(1 + \mu_i \times e^{-\frac{t}{\tau_i}}\right) \times A_{i,bui} \quad (7)$$

$$\Delta Q_{i,active}^{k} = u_i^k \times M_{i,w,max} \times C_p \times \left(T_{i,w,out}^{k} - T_{i,w,in}^{k}\right) - \varphi \times Q_{i,stored}^{k} \quad (8)$$

### *3.2. Game theoretic method to solve the cluster-level building demand management problem*

Game theory is the study of mathematical models of strategic interaction between rational decision-makers. It has applications in all fields of social science, as well as in logic and computer science. Originally, it addressed zero-sum games, in which one person's gains result in losses for the other participants. Today, game theory applies to a wide range of behavioral relations and is now an umbrella term for the science of logical decision making in humans, animals, and computers.

In this section, game theory is used to solve the problem of cluster-level building demand management. In a game, each player (i.e., building in the cluster) may partially or totally conflict with one another. They all want to maximize their own welfare by setting their strategies, that is, each building optimizes its own indoor air temperature set-point and the charging/discharging process of active thermal storage. A game $G$ consists of three components, that is, $G = \{\sigma, S, U\}$. Each player $i \in \sigma$ selects its strategy $s_i \in S$ to maximize its utility/welfare $u_i \in U$. The solution for this game is the Nash equilibrium, as defined in Eq.(9) [8].

*Definition*: A strategy vector $s^* = \{s_i^*, s_{-i}^*\}$ is a Nash equilibrium if and only if $\forall i \in \sigma$ and $\forall s_i \in S_i$, where $s_i$ is the player $i$'s strategy and $s_{-i}$ represents all of the other players' strategies.

$$U(s^*) \geq U(s_i, s_{-i}^*) \quad (9)$$

To identify the Nash equilibrium of the game related to the cluster-level building demand management, Nikaido-Isoda function is introduced for this study. This function transforms an equilibrium problem into an optimization problem [9]. According to the objective function of established game (i.e., Eq.(1)), the Nikaido-Isoda function $\Psi(x, y)$ is defined as Eq.(10). Where $U$ is equal to the opposite number of the objective function. $U(y_i|X) - U(X)$ presents the improvement for reducing the electricity bill when building $i$ changes its control action from $x_i \in X$ to $y_i \in Y$, while the control actions of the other buildings remain unchanged. Eq.(11) is the best response of buildings to maximize the utility function of the game facing the current given control signal $X$. Eq.(12) is the updated control signals of buildings for the next iteration. The iteration will be stopped until the Nikaido-Isoda function reaches the maximum. $\theta$ is a relaxation faction.

$$\Psi(X, Y) = \sum_{i \in \delta} [U(y_i|X) - U(X)] \qquad X, Y \in \vartheta, \quad Y = \{y_i | i \in \delta\} \quad (10)$$

$$Z(X) = argmax_{Y \in \vartheta}\, \Psi(X, Y) \qquad X, Z(X) \in \vartheta \quad (11)$$

$$X^{l+1} = (1 - \theta^l)X^l + \theta^l Z(X^l) \quad (12)$$

## 4. Test arrangement

The real data of building electricity on a Hong Kong campus were used to test the proposed control strategy for cluster-level building demand management. Hong Kong is a modernized city in a cooling dominated region with high power demands density. The buildings on the campus are mainly equipped with central air-conditioning systems. The electricity bill of the university charged by the power grid is divided into four accounts. One account involved four buildings was selected. The electricity charge tariff considers both energy consumption and peak demand into account, as shown in Table 1.

Table 1 The Hong Kong electricity charge tariff

| | Peak demand charge (*HKD/kW*) | | Total energy charge (*HKD/kWh*) | |
|---|---|---|---|---|
| | On-peak rate | Off-peak rate | On-peak rate | Off-peak rate |
| Time period | 9:00-21:00 | Other hours | 9:00-21:00 | Other hours |
| Price | 12 | 0.0 | 0.9 | 0.6 |

## 5. Results and discussion

Three control strategies were compared for optimizing the cluster-level building demand management, that is, the individual-level control strategy, game theoretic cluster-level control strategy, and centralized cluster-level control strategy.

Fig.2 shows the optimized cooling demands provided by the central air-conditioning systems of buildings associated to the campus account using different control strategies. The flexibility of building power demand was contributed by the cooling demand control of central air-conditioning system. During the high aggregated demand period (i.e., 15:00pm-16:00pm), the cooling demands of buildings were effectively reduced using two cluster-level control strategies. But the optimized results of cooling demands were obviously different when using the individual-level control strategy because their own peak demands of buildings were focused on, not the aggregated peak demand of the account.

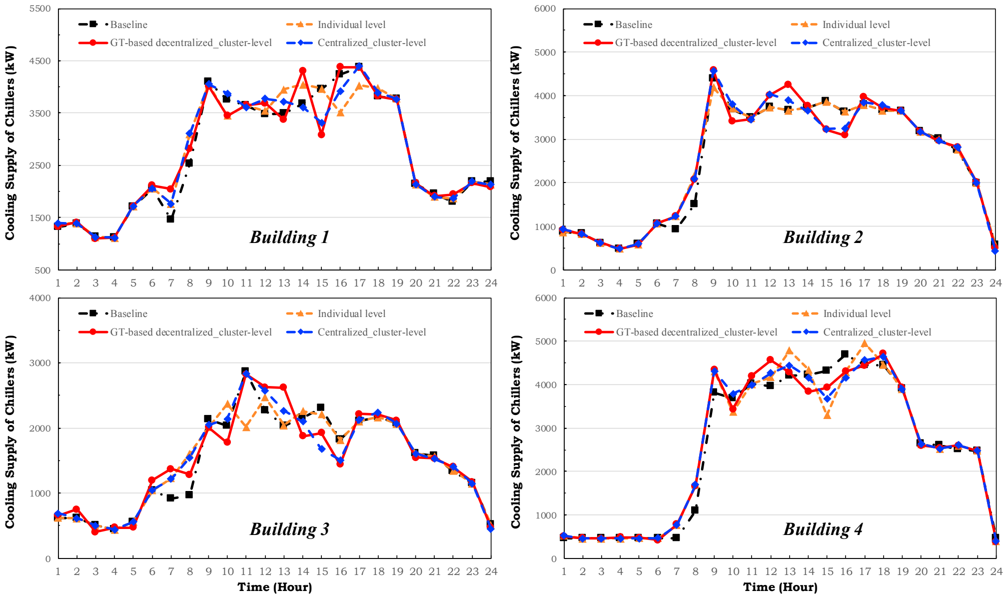


Fig.2 Optimized cooling demands for cluster-level buildings using different control strategies

The game theoretic decentralized control strategy could achieve a similar result with that using the centralized control strategy. The daily aggregated demands of the campus account using these two cluster-level control strategies were both maintained around 11,000kW. It worthy of note that the performance of centralized cluster-level control strategy was considered as the perfect results because the system information and measurements of all the buildings can be collected by a central control system. The peak demand optimized by the proposed game theoretic method was almost the same as the perfect result, which demonstrated its good control performance.

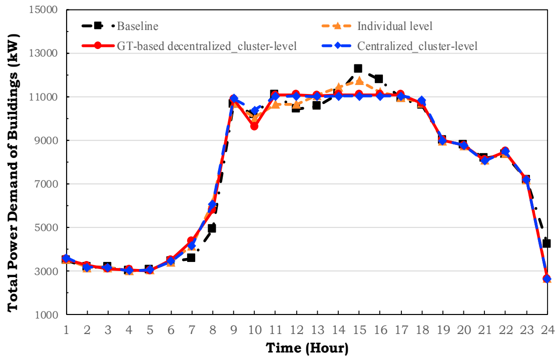


Fig.3 Optimized power demand management of cluster-level buildings using different control strategies

## 6. Conclusions

As supply side management becomes increasingly costly and technically more difficult, efforts from the demand side are more widely and commonly made. Based on real on-site data of building electricity on a university campus in Hong Kong, the shortage of cluster-level building demand management in an uncoordinated way was revealed. Therefore, this paper developed a game theory-based decentralized control strategy for cluster-level building demand management. The charging/discharging process of active thermal storage and building thermal mass were optimized simultaneously in each building to benefit the overall demand management objective of the building cluster.

The performance of the proposed game theory-based decentralized control strategy was tested and validated based on the real site data of building electricity. The optimized cooling demand contributed by the charging/discharging controls of active thermal storage and building thermal mass cannot effectively reduce the aggregated peak demand of the account when the optimization was proceeded in an uncoordinated way by individual-level control strategy. Using the game theory-based decentralized control strategy, the peak demand can be effectively reduced by about 10%, over two times than that using individual-level control strategy.

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