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Green Building Facilitated by Supply Demand Coordination in Microgrid

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Abstract: The energy consumption of building related to the occupant comfort behavior is consistently growing, but the energy generation system has limited capacity. It is therefore of great practical interest to achieve building energy savings through supply demand coordination and human building interaction. We consider this important problem in this paper. In particular we focus on zones that are shared by multiple occupants and make the following contributions. First, due to the difference among occupants, three cost structures are developed to discuss how the energy cost of the zone is shared among the occupants. Second, for each cost structure, a corresponding scheduling problem is formulated to minimize the overall energy cost considering the thermal comfort of the occupants. This problem is converted to a mixed integer programming, and solved by CPLEX. Third, numerical examples are used to compare the energy saving potentials under these cost structures. The impact of the occupant comfort model on the energy efficiency of the overall building and the choice of the storage devices capacities are also discussed. We hope this work brings insight on green buildings with group dynamics among occupants in more general situations.

1. INTRODUCTION

Recently building energy savings has attracted more and more attention due to the following reasons. First, according to the U.S. Department of Energy, about 40% of total energy is consumed on buildings in industrialized countries (Wetter and Polak, 2005), there is thus a huge potential for building energy savings. Second, energy consumption of building is consistently growing, but the energy generation system has limited capacity. Therefore, it is important to achieve the building energy savings through coordinating the demand and the supply in buildings. Furthermore, the energy demand of building is affected by the occupant comfort behavior which is subjected to the physiology of each occupant and the feedback information of the average price of electricity (APE) of multiple generation devices. It is therefore of great practical interest to achieve building energy savings through supply demand coordination and human building interaction.

This supply demand coordination and human building interaction problem is challenge due to the following difficulties. First, the variety in occupants' behaviors. In most office building, some occupants are assigned to one room, but each occupant has his/her own comfortable requirements which may be usually different from the one of each others. This causes a lot of energy waste in buildings, as well as dissatisfaction on comfort of each occupant. Second, the coupling between the supply and the demand. The schedule of the energy supply system is affected by the demand requirements which are related to the occupants comfort behavior. Meanwhile, the occupants comfort behavior is also affected by the APE of multiple generation devices. Moreover, multiple energy systems of buildings integrate the operation of electrical and thermal energy supply and demand, which are a microgrid. The supply may include power grid, autonomous power generators such as combined cooling, heat, and power (CCHP) systems, renewable energy resources such as PV panels and wind powers, and storage devices such as battery and ice storage. The demands may include heating ventilation air conditioner (HVAC), lighting, elevators, and IT data centers. Therefore, it is difficult to solve the joint scheduling problem due to the coupling in the supply and the demand and high-dimensional state space and action space. Third, the fairness in cost structure. Some of occupants lived in a room may feel comfortable, but other of them may feel uncomfortable at the same time since the temperature of indoor air can be set to only one value during each period. It is difficult to charge the energy cost for each occupant with his/her dissatisfaction on comfort fairly. Fourth, multi-stage decision making. The decision both in the supply and the demand not only affects the energy cost at this stage, but also affects the cost in future stages.

We consider this important problem in this paper. In particular we focus on zones that are shared by multiple occupants and make the following major contributions. First, due to the difference among occupants, three cost structures are developed to discuss how the energy cost of the zone is shared among the occupants. Second, for each cost structure, a corresponding scheduling problem is formulated to minimize the overall energy cost while considering the thermal comfort of all occupants located in the same room. This problem is converted to a mixed integer programming, and solved by the CPLEX solver. Third, numerical examples are used to compare the energy saving potentials under these cost structures. The impact of the occupant comfort model on the building energy savings and the choice of the storage devices capacities are also discussed.

The rest of the paper is organized as follows. We briefly review related literatures in section 2, mathematically formulate the problem in section 3, present the solution methodology and the three charge modes in section 4, discuss the numerical results in section 5, and briefly conclude in section 6.

2. LITERATURE REVIEW

The existing studies on building energy savings include two groups. The first group focuses on how to improve the building energy efficiency, and the second one focuses on quantifying and predicting the demand in buildings. In the first group, many efforts have been made to improve the building energy efficiency. On the one hand, some studies focus on improving energy efficiency of demand side in buildings, and there are three categories of methods in general. 1) Simulation based optimization method. This method is always combined with an energy simulation program and an optimization program (Wetter and Polak, 2005). 2) Model predictive control (MPC). Privara *et al.*, (2013) presented a new methodology to obtain a model suitable for the use in a predictive control framework combining the building energy performance simulation tools and statistical identification. 3) Schedule the subsystem of buildings (such as HVAC and lighting system) jointly or individually (Sun *et al.*, 2013). On the other hand, some efforts have been made to improve the energy efficiency of the building energy supply system. Guan *et al.*, (2010) developed a method to improve the building energy efficiency by microgrid. Marnay *et al.*, (2008) proposed an optimization approach for obtaining the control strategy of commercial-building microgrids with the distributed energy resources customer adoption model.

However, the comfort model of occupant is assumed to be a fixed set point or a comfortable range in the most of the aforementioned work. In the second group of the studies on building energy savings, they focus on how to obtain this set point or comfortable range according to statistical models. The PMV model (Fanger, 1970) is one such example, which uses a regress model to predict the probability of mean vote under different indoor temperatures. The comfortable difference of occupants which leads to concept of personalized comfort was not distinguished in these models. In recent years, some studies focus on achieving building energy savings with considering the personalized occupant comfort. E.g., Zhao *et al.*, (2011) developed a method to model the personalized human thermal comfort, and the dynamics and the individual differences with high correct probability can be captured by using this method.

In this paper, the idea of human building interaction with group dynamics among occupants will be explored. Specifically, the temperature of indoor air and the schedule of building energy systems are controlled with considering the difference of thermal comfort among the occupants seated in the same zone.

3. PROBLEM FORMULATION

As shown in Fig. 1, building energy systems are a microgrid that include renewable energy resources (such as PV panels), autonomous power generators (such as CCHP), and storage devices (such as battery and ice storage). Micro smart grid technology provides a desirable infrastructure for supply demand coordination and human building interaction in buildings. Particularly, in this paper we focus on one zone (room) that is shared by multiple occupants. The problem is considered as a discrete time version (i.e., 24 hours are discretized into K stages). In each stage, for each occupant, a comfort model is used to determine the dissatisfaction on temperature which is affected by the APE and the temperature of indoor air. The scheduling problem is formulated to minimize the overall energy cost shared among the occupants. The model of dissatisfaction on temperature for each occupant, the model of energy consumption in the room, the model of supply system dynamics, and the objective function are presented in subsection 3.1, 3.2, 3.3, and 3.4, respectively.

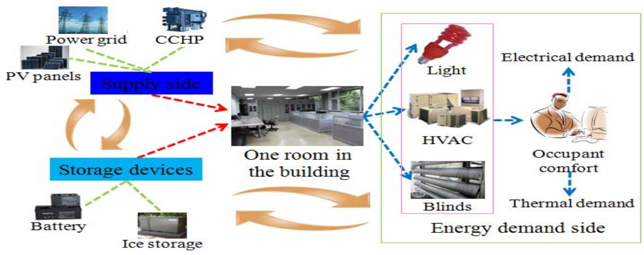


Fig. 1. A typical building energy systems.

3.1 Model of Dissatisfaction on Temperature for Occupant

The thermal comfort is the most important factor of the comfortable requirements in an indoor environment. So in this paper we focus on modeling the dissatisfaction on temperature for each occupant. For simplicity, it is assumed to be a piecewise linear function of the temperature of indoor air t_a^k, and the axis of the temperature is divided into five ranges including $[0, t_{aca})$, $[t_{aca}, t_{ac})$, $[t_{ac}, t_{ac1}]$, $(t_{ac1}, t_{acb}]$, $(t_{acb}, t_m]$. Furthermore, for each occupant, the comfortable range of temperature is affected by the feedback of electrical price (Peschiera *et al.*, 2010). The comfortable range $[t_{ac}, t_{ac1}]$ of each occupant is thus assumed to be the piecewise linear function of the APE $\tilde{c}^k$, so for occupant i we have

$$ucd_i^k = \begin{cases} 0 & if\ t_a^k \in [t_{ac,i}, t_{ac1,i}], \\ a_{t1} \cdot t_a^k + c_1 & if\ t_a^k \in (t_{ac1,i}, t_{acb,i}], \\ a_{t2} \cdot t_a^k + c_2 & if\ t_a^k \in [t_{aca,i}, t_{ac,i}), \\ a_{t3} \cdot t_a^k + c_3 & if\ t_a^k \in [0, t_{aca,i}), \\ a_{t4} \cdot t_a^k + c_4 & if\ t_a^k \in (t_{acb,i}, t_m], \end{cases} \quad (1)$$

$$[t_{ac,i}, t_{ac1,i}] = \begin{cases} [t_1, t_{1ac}] & if\ \ 0 \le \tilde{c}^k \le \tilde{c}_1 \\ [t_2, t_{2ac}] & if\ \ \tilde{c}_1 < \tilde{c}^k \le \tilde{c}_2 \\ [t_3, t_{3ac}] & if\ \ \tilde{c}^k > \tilde{c}_2 \end{cases} \quad (2)$$

where ucd_i^k is the dissatisfaction on temperature; a_{t1}, a_{t2}, a_{t3}, and a_{t4}, and c_1, c_2, c_3, and c_4 are the slope and intercept of the linear function for the corresponding range, respectively; t_1, t_{1ac}, t_2, t_{2ac}, t_3, and t_{3ac} are the given values of the comfortable range; $\tilde{c}_1$ and $\tilde{c}_2$ are given parameters of the APE. For a specific occupant, all the above parameters can be obtained with statistical methods (such as PMV model) and actual tests. This occupant comfort model can be used to capture the tradeoff between comfort in temperature and cost and describe the difference of comfortable range of temperature among the occupants.

The APE is defined as the following:

$$\tilde{c}^k = (p_d^k \cdot c^k + p_s^k \cdot c_s^k + p_b^k \cdot c_b^k + p_c^k \cdot c_c^k) / (p_d^k + p_s^k + p_b^k + p_c^k) \quad (3)$$

where p_d^k, p_s^k, p_b^k, and p_c^k are the electricity supplied by the power grid, the PV panels, the battery discharging, and the CCHP at k, respectively; c^k is the time of use(TOU) price for electricity per kWh at k; c_s^k, c_b^k, and c_c^k are the electricity generation cost per kWh of the PV panels, the battery discharging, and the CCHP at k, respectively.

In this paper, the dissatisfaction on temperature is assumed to be converted into the penalty cost ucp_i^k for dissatisfaction with the parameter A_i, and we thus have

$$ucp_i^k = A_i \cdot ucd_i^k \quad (4)$$

3.2 Model of Energy Consumption in the Room

A HVAC with independent control of temperature and humidity (Waugaman *et al.*, 1993) is used to provide and maintain the thermal environment of room shared by the multiple occupants. Since the thermal comfort is considered in this paper, the fan coil unit (FCU) used to control the temperature of indoor air is modeled in details. The coefficient of performance (COP) is used to estimate the energy efficiency of other parts in the HVAC.

Assume that there are one FCU in the room. The flow rate of FCU G^k usually takes four values, namely 0, 1/3, 2/3, and full of the rated flow rate in practice. x_{g1}^k, x_{g2}^k, and x_{g3}^k =1 if G^k =1/3, 2/3, and full of the rated flow rate, respectively; and 0 otherwise. When $x_{g1}^k = x_{g2}^k = x_{g3}^k = 0$, the FCU is shut down. g_1, g_2, g_3 =1/3, 2/3, and full of the rated flow rate, respectively. t_{af1}^k, t_{af2}^k, and t_{af3}^k is defined as the difference between the temperature of indoor air and the outlet of FCU when the flow rate of FCU is 1/3, 2/3, and full of its rated value, respectively. Assume there is sufficient humidity control capability when the indoor air temperature is within the required range. The cooling supplied by the FCU q_{fcu}^k and the electricity consumed by the FCU e_{fcu}^k at k is therefore given by

$$G^k = x_{g1}^k \cdot g_1 + x_{g2}^k \cdot g_2 + x_{g3}^k \cdot g_3, \quad x_{g1}^k + x_{g2}^k + x_{g3}^k \le 1. \quad (5)$$

$$t_{af1}^k + t_{af2}^k + t_{af3}^k = t_a^k - t_{fcu}^k \quad (6)$$

$$0 \le t_{af1}^k \le x_{g1}^k \cdot \overline{t_{af}},\ 0 \le t_{af2}^k \le x_{g2}^k \cdot \overline{t_{af}},\ 0 \le t_{af3}^k \le x_{g3}^k \cdot \overline{t_{af}}. \quad (7)$$

where t_{fcu}^k is the outlet temperature of the FCU at k; $\overline{t_{af}}$ is the upper bound of t_{af1}^k, t_{af2}^k, and t_{af3}^k.

$$q_{fcu}^k = (g_1 \cdot t_{af1}^k + g_2 \cdot t_{af2}^k + g_3 \cdot t_{af3}^k)(c_p + 1.84 h_k^a) \cdot \tau \quad (8)$$

where c_p is the specific heat of the air; h_a^k is the humidity of indoor air; τ is the length of time in each stage.

$$e_{fcu}^k = p_{rated} \cdot \sum_{j=1}^{3} x_{gj}^k \cdot (g_j / G_{rated})^3 \quad (9)$$

where p_{rated} is the rated power of the fan; and G_{rated} is the rated flow rate of the fan.

Assume that the indoor air is sufficiently mixed and thus has the same temperature in the room (Waugaman *et al.*, 1993). We thus have (Sun *et al.*, 2013)

$$\begin{aligned} m_a(t_a^{k+1} - t_a^k) &= \tau \cdot [I^k Q_g + Q_{light}^k + h_{gs} A_{gs}(t_o^k - t_a^k)] \\ &+ \sum_{j=1}^{6} h_{wj,in} A_{wj}(t_{wj}^k - t_a^k)] / c_p - \tau \cdot q_{fcu}^k / (c_p + 1.84 h_a^k) \end{aligned} \quad (10)$$

where m_a is the mass of the air; Q_g is the heat generation rate per person; h_{gs} is the convection coefficient between the window and the indoor air, A_{gs} is the area of the window; $h_{wj,in}$ is the convection coefficient between the wall j and the indoor air, A_{wj} is the area of wall j; I^k is the number of occupants in the room; Q_{light}^k is the heat generated by the lighting equipment; t_o^k is the temperature of outdoor air; t_{wj}^k is the temperature of internal surface of wall j, all at k.

The energy of the wall is affected by the heat convection with indoor air and outdoor air, solar heat gains on the exterior surface S_{out}, and the solar heat gains incident through the window on the interior surface S_{in}. Then, for each wall we have

$$c_w m_{wj}(t_{woj}^{k+1} - t_{woj}^k)/\tau = h_o A_{wj}(t_o^{k+1} - t_{woj}^k) + \frac{\kappa}{l_{wj}} \cdot A_{wj} \cdot (t_{wj}^{k+1} - t_{woj}^k) + S_{out} \quad (11)$$

$$c_w m_{wj}(t_{wj}^{k+1} - t_{wj}^k)/\tau = h_{wj,in} A_{wj}(t_a^{k+1} - t_{wj}^k) + \frac{\kappa}{l_{wj}} \cdot A_{wj} \cdot (t_{woj}^{k+1} - t_{wj}^k) + S_{in} \quad (12)$$

where c_w is the specific heat of the wall; m_{wj} is the mass of the wall j; t_{woj}^k is the temperature of exterior surface of the wall j at k; h_o is the convection coefficient between the wall and the outdoor air; κ is thermal conductivity of the wall; and l_{wj} is thickness of the wall j.

The daylight I_d^k and lighting equipment I_{light} are used to provide the comfortable illuminance in the room, so we have

$$I_d^k + e_{light}^k \cdot I_{light} \ge I_{load}, \qquad Q_{light}^k = e_{light}^k \cdot \mu_l / \tau. \tag{13}$$

where e_{light}^k is the electricity consumed by lighting equipment at k; I_{load} is the illuminance demand; and μ_l is the parameter of lighting equipment.

3.3 Model of Supply System Dynamics

a) Energy balance equations

1) Electrical balance

$$p_d^k + p_u^k + p_s^k + p_c^k + p_b^k - p_{bc}^k = e_{hvac}^k + e_{ice}^k + e_{light}^k + e_{fcu}^k \tag{14}$$

where p_u^k and p_{bc}^k are the electricity fed into the grid and charged into the battery at k, respectively; e_{hvac}^k and e_{ice}^k are the electricity consumed by the chiller in the refrigeration mode and the ice-making mode at k, respectively.

2) Cooling balance

$$q_c^k + e_{hvac}^k \cdot COP + e_{ice}^k \cdot COPI = q_{fcu}^k + q_i^k \text{-} q_{id}^k \tag{15}$$

where q_c^k is the cooling supplied by CCHP at k; COP and $COPI$ are the COP of the chiller in the refrigeration mode and in the ice-making mode, respectively; q_i^k and q_{id}^k are the cooling charged to and discharged from the ice storage, respectively.

b) Cost of electricity and natural gas

1) Cost of electricity $C_p^k(c^k, c_u^k, p_d^k, p_u^k)$

$$z_{pd}^k + z_{pu}^k \le 1,\;\; 0 \le p_d^k \le z_{pd}^k \cdot M,\;\; -M \cdot z_{pu}^k \le p_u^k \le 0. \tag{16}$$

$$C_p^k(c^k, c_u^k, p_d^k, p_u^k) = p_d^k \cdot c^k + p_u^k \cdot c_u^k \tag{17}$$

where z_{pd}^k (or z_{pu}^k) =1 if electricity is bought from (fed into) the power grid at k, and 0 otherwise; M is a sufficiently large positive integer; and c_u^k is the selling price of electricity at k.

2) Cost of natural gas $C_n^k(c_n^k, V_c^k)$

$$C_n^k(c_n^k, V_c^k) = c_n^k \cdot V_c^k \tag{18}$$

where c_n^k is the price of natural gas at k, and V_c^k is the natural gas consumed by CCHP at k.

c) System dynamics of battery

1) Input and output power capacities

$$z_{bc}^k + z_{bd}^k \le 1,\; p_b^k / \tau \in z_{bd}^k \cdot [\underline{p_{bo}}, \overline{p_{bo}}],\; p_{bc}^k / \tau \in z_{bc}^k \cdot [\underline{p_{bi}}, \overline{p_{bi}}] \tag{19}$$

where z_{bc}^k (or z_{bd}^k) =1 if the battery is charged (discharged) at k, and 0 otherwise; $\underline{p_{bi}}$ and $\overline{p_{bi}}$ ($\underline{p_{bo}}$ and $\overline{p_{bo}}$) are the lower and upper bound of the charge (discharge) rate, respectively.

2) State of charge (SOC) dynamics

$$x_b^{k+1} = x_b^k - (p_b^k + p_{bc}^k) / \overline{e_b}\;,\;\; \underline{x_b} \le x_b^k \le 1,\quad x_b^o = x_b^K = x_{bi} \tag{20}$$

where x_b^k is the SOC of battery at k; $\overline{e_b}$ is the capacity of battery; $\underline{x_b}$ and x_{bi} is the lower bound and the initial value of SOC, respectively.

3) Penalty for cycle lifetime

$$z_{bc,c}^k + z_{bc,d}^k \le 1,\;\; z_{bc,c}^k + z_{bc,da}^k \le 1,\;\; z_{bc,ca}^k + z_{bc,d}^k \le 1. \tag{21}$$

$$z_{bc}^k - z_{bc}^{k-1} = z_{bc,c}^k - z_{bc,da}^k,\quad z_{bd}^k - z_{bd}^{k-1} = z_{bc,d}^k - z_{bc,ca}^k \tag{22}$$

$$C_b^k = [z_{bc,c}^k + z_{bc,d}^k] \cdot (b_c / b_l) \tag{23}$$

where $z_{bc,c}^k$ (or $z_{bc,d}^k$) =1 if the battery starts charging (discharging) at k, and 0 otherwise; $z_{bc,ca}^k$ and $z_{bc,da}^k$ are the parameters to balance (22); C_b^k is the penalty at k; b_c and b_l are the investment cost and life-time of battery, respectively.

d) System dynamics of CCHP (Guan *et al.*, 2010)

1) Constraint of the operation of the CCHP

$$z_c^k \cdot \underline{x_c} \le x_c^k \le z_c^k \cdot \overline{x_c} \tag{24}$$

where $z_c^k = 1(or\ 0)$ if CCHP is started up (or shut down) at k; x_c^k is the electrical load ratio of CCHP during k.

2) Output energy of the CCHP

$$p_c^k = \overline{p_c} \cdot x_c^k \cdot \tau, \quad q_c^k = (a \cdot x_c^k + b \cdot x_c^k) \cdot \tau \tag{25}$$

3) Consumption of natural gas

$$V_c^k = (c \cdot x_c^k + d \cdot z_c^k) \cdot \tau \tag{26}$$

Note that a, b, c, and d are parameters of the CCHP that are obtained by linear fitting (Guan *et al.*, 2010).

e) System dynamics of the HVAC (including ice storage)

1) Constraint of the operating mode of the chiller

$$z_{hvac}^k + z_{ice}^k \le 1 \tag{27}$$

where z_{hvac}^k (or z_{ice}^k) =1 if chiller works in refrigeration (ice-making) mode, and 0 otherwise.

2) Cooling power generation in two modes

$$e_{hvac}^k \cdot COP \le z_{hvac}^k \cdot q_{hvac} \cdot \tau, \quad e_{ice}^k \cdot COPI \le z_{ice}^k \cdot q_{hvac} \cdot \mu \cdot \tau \tag{28}$$

where μ is efficiency of the chiller works in ice-making mode.

3) Dynamics of the remaining cooling in the ice storage

$$q_{io}^{k+1} = (q_{io}^{k} + q_{i}^{k} - q_{id}^{k}) \cdot \mu_{q} \quad (29)$$

where q_{io}^{k} is the remaining cooling and μ_q is the dissipation coefficient of cooling.

The solar power generation of PV panels is obtained through the model and parameters developed in Wang *et al*., (2008).

3.4 Objective Function

Assume that there are I occupants located in the room, the objective function is:

$$\min J, \text{with } J = \sum_{k=1}^{K} \left\{ [C_p^k(\cdot) + C_n^k(\cdot) + C_b^k] + \sum_{i=1}^{I} ucp_i^k \right\} \quad (30)$$

4. SOLUTION METHODOLOGY

Equations (1)-(3) are non-linear. They can be linearized by introducing some integer variables. The linearization of (1)-(3) can be found in our related work (Xu *et al*., 2013), and it is thus omitted in this paper. Due to the difference of comfort in temperature among the multiple occupants in the room, three cost structures are developed to discuss how the energy cost of the zone is shared among the occupants. The three cost structures are named CS1, CS2, and CS3, respectively. The definitions of them are presented in the following.

CS1. Under this cost structure, the penalty cost for dissatisfaction on temperature of each occupant is considered. At each stage, the occupants who feel comfortable should pay for the penalty cost generated by the occupants who feel uncomfortable. This penalty cost is shared equally among the comfortable occupants, and it is provided to the uncomfortable occupants as the compensation. The objective function of the scheduling problem of this structure is described in (30).

CS2. Under this cost structure, the penalty cost for dissatisfaction on temperature is not considered. The comfortable range $[t_{cs2}, t_{cs2a}]$ varied with the APE is used to indicate the union set of the comfortable range of all occupants seated in the room. The scheduling problem is solved with the range $[t_{cs2}, t_{cs2a}]$ as a given one. The objective function of this structure is thus

$$\min J_1, \text{with } J_1 = \sum_{k=1}^{K} [C_p^k(\cdot) + C_n^k(\cdot) + C_b^k] \quad (31)$$

CS3. Under this cost structure, the penalty cost for dissatisfaction on temperature is also not considered. tcs3 varied with the APE is used to indicate the midpoint of the comfortable range of all occupants seated in the room. The scheduling problem is solved with this given set point, and the objective function is the same as (31).

Note that the scheduling problem is solved with considering the human building interaction, with the given comfortable range of temperature, and with the fixed set point of temperature under CS1, CS2, and CS3, respectively. The scheduling problem of (1)-(30) under CS1, and the scheduling problem of (1)-(29) and (31) under CS2 and CS3 are mixed integer programming problems and can be solved by the CPLEX solver. Numerical examples are used to compare the performance difference of the three cost structures and analyze the energy saving potential under these structures in section 5.

5. NUMERICAL RESULTS

A room shared by ten occupants is tested, and it is 10 meters long, 5 meters wide, and 4 meters high. Assume that the room is occupied from 7:00 to 24:00. The test is carried out for a hot and humid summer day in Beijing, and the weather data is obtained from *Website of China Meteorological Administration*. The supply energy systems of the room include the power grid, the PV panels (14 cells in series), one CCHP unit (rated power of 5 kW), one battery (capacity of 0.4 kWh), and one ice storage device (capacity of 18 kWh). The rated power of chiller of the HVAC is 3 kW, and the rated flow rated of the FCU is 1160 m^3/h. The price of natural gas is 2.05 RMB/m^3. The selling price of electricity fed into grid is 0.457 RMB/kWh. The TOU price of Beijing is shown in the following Table

Table 1. Beijing TOU electricity price

Periods	TOU price (RMB/kWh)
0:00 – 7:00, 23:00 – 24:00	0.3515
7:00 – 11:00, 19:00 – 23:00	0.8135
11:00 – 19:00	0.4883

Assume that ten occupants seated in the room are divided into three groups including the frugal one (named G1), the neutral one (named G2), and the profligate one (named G3). The comfortable ranges of three groups affected by the APE are shown in Table 2. Assume that t_{aca} and t_{acb} are equal to t_{ac} minus 2 and t_{ac1} plus 2, respectively. The slopes in five ranges including $[0, t_{aca})$, $[t_{aca}, t_{ac})$, $[t_{ac}, t_{ac1}]$, $(t_{ac1}, t_{acb}]$, $[(t_{acb}, t_m]$ are -0.4, -0.1, 0, 0.1, and 0.4, respectively. The comfortable ranges $[t_{cs2}, t_{cs2a}]$ under CS2 and t_{cs3} under CS3 in this test are thus [22 °C, 28 °C], [23 °C, 28 °C], and [24 °C, 28 °C] and 26 °C, 26.6 °C, and 27 °C, respectively, when the APE is within [0, 0.42], (0.42, 0.65], and (0.65, +∞).

Table 2. Comfort range of the three groups

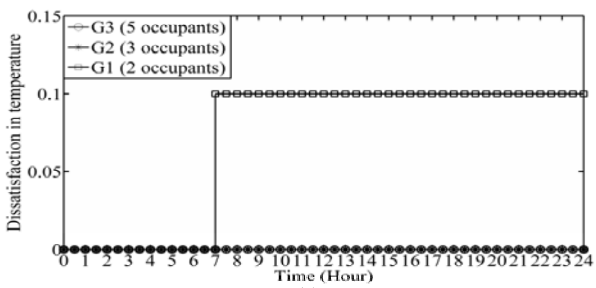
APE (RMB/kWh)	[0, 0.42]	(0.42, 0.65]	(0.65, +∞)
G1(°C)	[25, 28]	[26, 28]	[27, 28]
G2(°C)	[24, 26]	[25, 27]	[25, 27]
G3(°C)	[22, 24]	[23, 25]	[24, 26]

5.1 Performance Comparison under CS1, CS2 and CS3

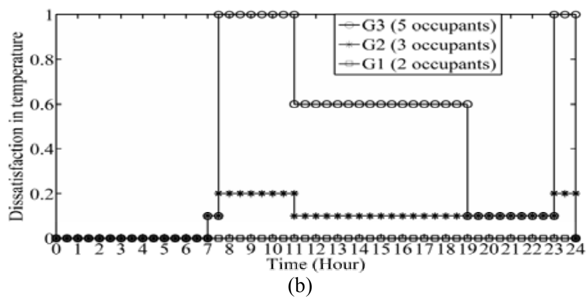
The scheduling problem is performed under the three cost structures, respectively. Assume that G1, G2, and G3 include two occupants, three occupants, and five occupants, respectively. The CPLEX solver is used to solve the problem, and the relative error gap is set as 0.01. By using a Windows PC with 3.2 GHz CPU and 4 GB memory, it took 47s, 18s, and 27s to finish each calculation under CS1, CS2, and CS3, respectively. The energy cost for each cost structure is shown in Table 3, and the dissatisfaction on temperature for each group of the occupants under CS1, CS2, and CS3 are shown in Fig. 2 (a), (b), and (c), respectively. The temperature curves of indoor air obtained under the three cost structures are shown in Fig 2 (d).

As shown in Table 3 and Fig 2, under CS1, the overall energy cost is relatively high, but only two occupants feel uncomfortable during the occupied time. Under CS2, although the energy cost is the lowest one under the three cost structures, almost everyone in the room (eight occupants) feel uncomfortable. The performance of the dissatisfaction on temperature under CS3 is between the one under CS1 and CS2. In this case, it is found that the more energy savings can be achieved with the given comfortable range, but the comfortable requirement of each occupant seated in the same room cannot be guaranteed. Therefore, we should consider the human building interaction for each occupant to capture the individual difference on comfortable range of temperature in building energy savings, such as solution under CS1.

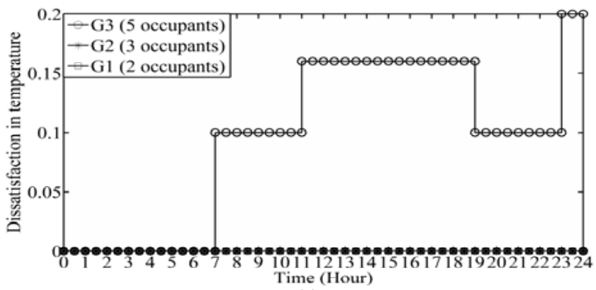
The APE under each cost structure is shown in Fig. 3, respectively. Under CS1, in order to make the major occupants feel comfortable, the APE is adjusted within the range of (0.65, +∞) through scheduling the energy supply system with the storage devices during the occupied time. Under CS2 and CS3, through adjusting the APE, the given comfortable range of CS2 and the set point of CS3 are within the higher range or equal to higher set point to reduce the energy cost during the peak-price periods.



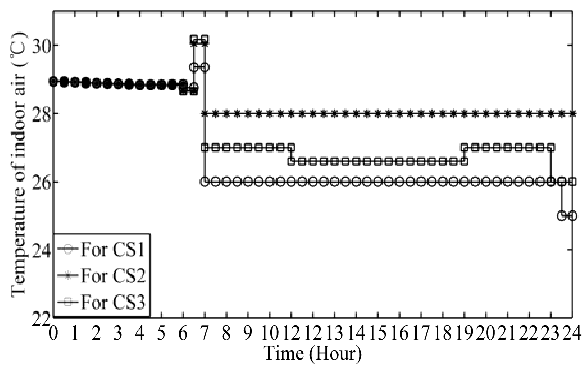
(a)



(b)



(c)



(d)

Fig. 2. (a) The dissatisfaction in temperature for CS1; (b) The dissatisfaction in temperature for CS2; (c) The dissatisfaction in temperature for CS3; (d) The temperature of indoor air.

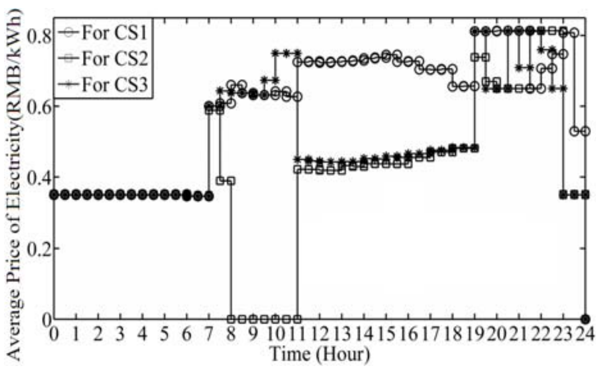


Fig. 3. The APE for each cost structure.

Table 3. Energy cost under three cost structures

Cost structure	CS1	CS2	CS3
Overall energy cost (RMB)	17.52	10.52	18.24

As a comparison, another combination of occupants is tested. In this case, G1, G2, and G3 include five occupants, three occupants, and two occupants, respectively. The energy costs under CS1, CS2, and CS3 are 12.76 RMB, 10.52 RMB, and 18.24 RMB, respectively. The energy cost under CS1 is reduced sharply, since the temperature of indoor air is controlled according to the comfortable ranges of G1 and G2. The two occupants of G3 are thus uncomfortable in this case. Under CS1, it is found that a tradeoff between the energy cost and the dissatisfaction on temperature is made. The comfortable requirement of major occupants can be satisfied under CS1, although the energy cost is relatively higher. It is also found that the energy cost under CS1 is sensitive with respect to difference in comfortable requirement of all occupants located in the same room. Furthermore, if somebody wants to set the temperature of indoor air according to his/her comfortable requirement under CS1, he/she should pay more fee which is provided to other occupants as the compensation. Under CS2 and CS3, the energy cost is the same as the one of previous case, since both the given comfortable range of CS2 and the set point of CS3 are not changed. But the number of uncomfortable occupants under CS2 and CS3 are changed, and they are 5 and 2, respectively. It is found that the number of uncomfortable occupants under CS2 and CS3 are both sensitive with respect to difference in combination of the occupants who share the same room.

5.2 Impact of the Occupant Comfort on the Energy Efficiency and the Choice of the Storage Devices

In this subsection, the impact of the occupant comfort on the energy efficiency and the choice of the storage devices for each cost structure will be discussed. The energy efficiency of the storage devices including the battery and the ice storage are shown in Table 4. In this paper, the energy efficiency of a specific storage device is defined as the ratio of overall cost savings with this storage device to that without the one. As shown in Table 4, it is found that the energy efficiency of the two storage devices is different from each other under the three cost structures, respectively. Under CS2, no matter how the APE changes, the upper bound of the comfortable range is 28 ^{o}C. The battery and the ice storage are thus only used to achieve the energy cost savings under this structure. So the energy efficiency of the two storage devices under CS2 is the highest one of the three structures. However, under CS1 and CS3, the energy efficiency of two storage devices is relatively lower, since the two storage devices are not only used to save energy cost, but also used to adjust the APE to change the comfortable range of occupants. Consider the investment cost of the storage devices, the optimal or necessary capacities of the battery (and the ice storage) under CS1, CS2, and CS3 are 0.2 kWh, 0.4 kWh, and 0.27 kWh (and 14.2 kWh, 18 kWh, 12.7 kWh), respectively. Therefore, when we allocated and control the storage devices in the building energy supply systems, the cost structure and the comfortable range of each occupant affected by the APE should be considered, i.e., the supply demand coordination and the human building interaction should be considered in building energy savings.

Table 4. Energy efficiency of the storage devices under each cost structure

	CS1	CS2	CS3
Battery	1.88%	5.18%	3.51%
Ice stoarge	10.18%	13.72%	9.72%

6. CONCLUSIONS

Significant portion of energy is consumed in building to provide and maintain the required indoor environment. In this paper, we consider a problem of supply demand coordination and human building interaction to achieve building energy savings. Three cost structures are defined, which is used to determine how the energy cost of the room is shared among the occupants seated in the room, according to their thermal comfort ranges, the indoor environment, and the APE. The scheduling problem under each cost structure is formulated as a mixed integer programming and solved by the CPLEX solver. The comparison and the performance difference of the three cost structures are shown using the numerical examples. The numerical results also show that the supply demand coordination and the human building interaction should be considered when we allocate and schedule the energy supply systems, especially, the storage devices.

The weather data and the comfortable range of each occupant are fixed in this paper. However, in practice, there are uncertainties in them. For example, the outdoor temperature is affected by the weather conditions such as clouds and solar radiation. The comfortable range of occupants may be changed with their physiology. Therefore, an interesting future work of this study is to consider the scheduling problem with uncertainties in the weather data and occupants.

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