Relationship between arrangements of houses with air-conditioners and usage of electric power

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ABSTRACT

Usually, the outside temperature of a house increases when we use the air-conditioner because of the outdoor unit. Consequently, usage of electric power consumed in an area raises because neighbor houses also start using air-conditioners to keep the inside temperature. Influence of this phenomenon could depend on the arrangement of the houses in the area. Thus, relationship between arrangement of houses with air-conditioners and electric power usage of a target urban area is investigated. A house with air-conditioner and an outdoor unit is represented as a mathematical model, and multi-agent simulations has been conducted with the model in order to investigate the relationship between arrangement of houses and usage of electric power. Effective arrangements of houses and ineffective arrangements of houses has been found by using random search method. As a result, there is a significant difference between the two types of arrangements. It has also become clear that usage of electric power decreases when houses with low preset temperature get closer with each other, on the contrary, usage of electric power increases when they get far from each other.

KEYWORDS

Multi-agent simulation, electric power consumption, hexagonal binning plot, convergence of houses

1 INTRODUCTION

In Japan, usage of home electric power has been increasing year by year [2]. Since the East Japan Earthquake on March 11th, 2011, Fukushima Daiichi nuclear power plant has been damaged, and all of the nuclear power stations in Japan have been deactivated. As a result, electric power cost for daily life has been increasing, and many people start to pay attention to electricity saving, especially during using air-conditioners.

According to the guideline which provided by Japan’s Ministry of health, Labour and Welfare, preset temperature of an air-conditioner should be set at 28 °C for saving electricity [1]. However, it is also argued that it could give negative effects to human’s health to set preset temperature of an air-conditioner excessively [3]. “Guideline of prevention of heat disorder in daily life [3]” declares that 28 °C is a seriously dangerous temperature condition for human’s health. According to the guideline, when preset temperature is beyond 28 °C, risk of heat disorder gets greater.

The following facts should be considered as typical problems of using air-conditioner. When an air-conditioners start to work, the outside temperature increases due to the heat air exhausted from the outdoor unit. Then, air-conditioners in the other houses are also turned on. As a result, the usage of electric power of the area increases because of the chain reaction. Of course, when distance between each house becomes further, the effect of exhaust heat gets weaker. However, distance between each house cannot be extended easily in urban area because of the limited space.

Therefore, a method of reducing usage of electric power by altering locations of houses in a limited area is required. Relationship between arrangements of houses with an air-conditioner and usage of electric power in the area is investigated. Features of the effective arrangements are also discussed.

For the above purposes, a representation model of a house which has an air-conditioner and an outdoor unit is proposed. Computer simu-
lations are conducted in order to observe usage of electric power in an area by using the proposed model. Effective arrangement of houses and ineffective arrangement of houses are found by using random search, and they are compared.

2 RELATED WORKS

An intelligent agent is usable to conduct a flexible and autonomous activity within a dynamic, unpredictable, and typically multi-agent domain [4]. Multi agent-based modeling or multi-agent system has been widely applied for problems in various fields including energy efficiency management.

For example, a multi-agent based intelligent control system is developed for achieving effective energy and comfort management in a building environment [5]. The developed multi-agent system turns out to be capable of facilitating the building to interact with its residents for realizing user-centered control of buildings [5].

Daraiseh et al. [6] have proposed an intelligent agent-based system to optimize energy consumption of Heating Ventilation and Air Conditioning systems in a higher education institutions buildings.

Urano et al. [7] have been created a model to investigate the effect of thermal environment in an urban area on energy consumption of buildings.

All of these studies focus on electric power cost of a building. In contrast, this study focuses on electric power cost of an area which has houses with an air-conditioner.

3 MATHEMATICAL MODEL AND SIMULATION

In this section, the design of the model, which stands for a house with an air-conditioner and an outdoor unit, is described. The procedure of the simulation is also described.

3.1 Model of house with air-conditioner and outdoor unit

The proposed model consists of 6 properties, which are $T^a_i$ (inside temperature), $T^a_p$ (preset temperature), $\Delta E^a$ (usage of electric power), $h(t)$ (temperature without exhaust heat), $T^a_o$ (outside temperature) and $T^a_e$ (temperature of exhaust heat).

- **Inside temperature: $T^a_i$**

$T^a_i$ means temperature in the room of agent $a$ when air-conditioner is not working. $T^a_i$ increases depends on $T^a_o$. $T^a_i$ is going down to the $T^a_p$ when air-conditioner starts working. $T^a_i$ at $(t + 1)$ is given by

$$T^a_{i,t+1} = T^a_{i,t} + \beta(T^a_o - T^a_{i,t}),$$  (1)

where $\beta$ is a coefficient of heat conduction of the wall. In this study, we use $\beta = 0.25$ as the constant.

- **Preset temperature: $T^a_p$**

$T^a_p$ means an air-conditioner’s preset temperature of agent $a$. In this study, $T^a_p$ is assigned in accordance with the results of “Research of preset temperature with air-conditioners in summer season” by Daily life and culture laboratory of Kirin shown in Fig 1 as graphs [8].

![Figure 1. Preset temperature of air-conditioner of Japanese aged 20 years and older (summer of 2008)]
Usage of electric power: $\Delta E^a$

$\Delta E^a$ means agent $a$’s consumed electric power of an air-conditioner for one hour. Air-conditioner starts working when $T_i^a$ is higher than $T_p$. It is computed by

$$\Delta E^{a,t} = \begin{cases} \alpha(T_i^{a,t} - T_p) & (T_i^{a,t} > T_p) \\ 0 & (T_i^{a,t} \leq T_p) \end{cases} \tag{2}$$

in which $\alpha$ is a constant which stands for necessary electric power consumed when $T_i$ decreases $1^\circ$C. In this study, $\alpha = 100$ is used.

Temperature without exhaust heat: $h(t)$

$h(t)$ represents the outside temperature at $t$ which is not effected by $T_e^a$. $h(t)$ changes as same as the graph shown in Fig. 2, which represents the average temperatures of August, 2014 in Tokyo [9] provided by Japan Meteorological Agency of Ministry of Land.

![Figure 2. Average temperature changing in a day in Tokyo, 2014](image)

Outside temperature: $T_o^a$

$T_o^a$ means temperature around a house agent $a$. $T_o^a$ changes because of $h(t)$ and other houses’ exhaust heat. It is computed by

$$T_o^{a,t} = h(t) + \gamma(T_e^{a,t} - h(t)), \tag{3}$$

where $\gamma$ means coefficient of heat conduction of the air, and $\gamma = 0.2$.

Temperature of exhaust heat: $T_e^a$

$T_e^a$ means an outside temperature of a house agent $a$ after getting effects from heat of the other agents’ outdoor units. The value of $T_e^a$ is determined from the gap between $T_i^a$ and $T_p^a$, and distance from other houses. $T_e^a$ at $(t + 1)$ is defined by

$$T_e^{a,t} = \max_{\forall x \in \text{all agent, } x \neq a} [(F_{x,t}^{a,t-1} - T_o^{a,t-1}) \times g(d)] + T_o^{a,t-1} \tag{4}$$

where $F_{x,t}^{a,t}$ is a function which represents a temperature of exhaust heat of a house agent $x$ at $t$. $F_{x,t}^{a,t}$ is defined as

$$F_{x,t}^{a,t} = (T_{e,\text{max}} - T_o^x) \times f + T_o^x \tag{5}$$

where $T_{e,\text{max}}$ is a constant which represents the maximum temperature of exhaust heat from the outdoor unit. In this study, $60^\circ$C is employed as the value in accordance with specification of usual home air-conditioners. $f$ is a function which represents power of heat from the outdoor unit. The gap between $T_i$ and $T_p$ gets bigger, the value of this function gets closer to 1. $f$ is defined as shown in Eq. 6

$$f = 2 \frac{1}{1 + e^{-0.3(T_i - T_p)}} - 1 \tag{6}$$

$g(d)$ is a function which represents attenuation effect of $T_e^a$ by considering distance between different agents $x$. When houses are getting further from each other, the effect of exhaust heat gets weaker. $g(d)$ is computed by

$$g(d) = \frac{1}{2.5d + 1}, \tag{7}$$

where $d$ means distance between agent $a$ and agent $x$.

3.2 Behavior of agents

Rule of agents’ actions

Each agent determines it’s behaviors based on relationships between $T_p$ and $T_i$. The rules of agents’ behaviors are shown below.

- Condition 1 : $T_p < T_i^t$
Action: The air-conditioner is operating.
Result 1: Electric power is consumed.
Result 2: $T_t$ increases.
Result 3: $T_t$ changes to $T_p$.

- Condition 2: $T_p \geq T_t$

Action: The air-conditioner is not operating.
Result 1: Electric power is not consumed.
Result 2: $T_t$ does not increase.
Result 3: $T_t$ increases due to effect of other agent’s $T_e'$.

### Flow of agents’ action

The process of the agents’ action is shown as a flowchart in Fig. 3.

1. Start
2. $T_t = T_t - 1 = T_i + \beta (T_o - T_i)$
3. $T_p < T_i$
4. $\Delta E = \alpha (T_i - T_p)$
5. $T_i = T_p$
6. $E_t + 1 = E_t + \Delta E_t$
7. $T_e = F_t - G_t - T_o$
8. $T_o = h_t + \gamma (T_e - h_t)$
9. Step $= S$
10. $S = S + 1$
11. Stop

The detail is described as the following steps: $E^t$ means usage of total electric power. $S$ means number of iterations. $t$ means the current time (step).

1. Agents are arranged randomly.
2. $T_o^t$ is affected by $T_i^t$.
3. Compare $T_i^t$ with $T_p^t$.
4. Electric power is consumed.
5. Value of $T_i^t$ changes to be value of $T_p$.
6. “Usage of total electric power” is added in $\Delta E^t$.

(7) $T_e^t$ is determined by distance between each house and “gap between $T_i^t$ and $T_p^t$”.

(8) $T_o^t$ is calculated.

(9) Compare $S$ with current steps.

(10) Current step is incremented.

(11) “Usage of total electric power” is observed at the end of sampled day.

### Relationships among agents

Relationships among each variable are shown in Fig. 4. In this figure, $A$ and $A'$ stand for a different house agent. Each node indicated by blue square means a properties of agents. Each arrow shows direction of the effect. The effects are explained as below.

1. $T_i$ changed by $T_o$.
2. $\Delta E^t$ is determined by differential of $T_i^t$ minus $T_p$.
3. If $\Delta E^t$ is positive number, $T_i^t$ will change to value of $T_p$.
4. “Usage of total electric power” increases.
5. $T_e^t$ is determined from $\Delta E^t$.
6. $T_o^t$ is determined by “the other agent’s exhaust heat ($T_e'$).”

![Figure 3. Process of action of agents](image)

![Figure 4. Relationship between two agents](image)
3.3 Generating effective and ineffective arrangement

In order to find effective/ineffective houses’ arrangements which provide less usage of electric power, a random search method is employed. The flowchart shown in Fig. 5 represents the process of the random search method. Step means times of iteration. S means the maximum times of iteration. Condition A and B means arrangements of houses in the area. Result A and B means electric power consumed under condition A and B respectively. r means search range, and agents are moved randomly within this range from the original positions in the previous step. i means times of searching with the same situation.

(7) The process is iterated S times.

The process which is indicated by I in Fig. 5 is introduced for avoiding local minimum. Eq. 8 shows search range used in this process. r changes depending on times of searching with the same condition.

\[
    r = \begin{cases} 
    0.5 & (i < N) \\
    5 & (i \geq N) 
    \end{cases} 
\]

\[N = 25.\]

4 EXPERIMENT

Arrangements with less and more usage of electric power consumed by air-conditioners are compared. Artisoc [10], which is a multi-agent simulation environment, is used for the experiments.

4.1 Configuration of experiments

Conditions of the experiment are shown below.

- Number of agents : 220
- Number of iterations : 1,000

Agents are generated as defined in the section 3. Target space is a $15 \times 15$ two-dimensional area. The house agents are not effected from outside of the space. Usage of electric power in the area is calculated while one thousand times iteration. The experiments have been conducted for 10 times with searching arrangements of less and more electric power usage respectively.

4.2 Results of experiments

The results of the experiments are shown in Table 1 and 2. Table 1 shows the usage of electric power of effective houses arrangements and Table 2 shows the usage of electric power of ineffective houses arrangements. In these tables, each line labeled by $E$ means usage of total electric power.
There is significant difference between the two types of arrangements (\( t = 20.34, p < 0.01 \)). Thus, we could get effective/ineffective arrangements of houses for usage of electric power.

5 DISCUSSION

The relationship between convergence of each house and the usage of electric power is analyzed. Convergence of agents with \( T_p \) of 18 °C is analyzed because surrounding agents are mostly effeted by the agent which holds 18 °C as \( T_p \).

5.1 Hexagonal binning plot

In order to investigate convergence of houses, Hexagonal binning plot [11] is used. The brightness value of each hexagonal cell is determined by the number of agents in the cell. Fig. 6 shows an example of analyzing convergence situation. Dots in the figure are agents which set preset temperature to 18 °C. When color of hexagonal cell is darker, it means that there are more agents in the hexagonal area. Fig. 7 illustrates the meaning of the color of hexagonal cells. Convergence is analyzed by counting the number of hexagonal cells. In this paper, 4 cases with 6 sizes of hexagonal cells, \( l = 3.75 \) (case 1), \( l = 3.00 \) (case 2), \( l = 2.50 \) (case 3), \( l = 2.14 \) (case 4) are used for analyzing convergence situation. Here, \( l \) means width between parallel edge of a hexagonal cells. Fig. 8 shows the examples of the cases.

5.2 Convergence of agents

Comparison of number of agents in a hexagonal cells are shown as bar graphs in Fig. 9 to Fig. 12. The vertical axes mean average number of hexagonal cells, and the horizontal axes mean number of agents in hexagonal cells. “Effective arrangement” means average number of hexagonal cells in the arrangements with less usage of electric power, and “Ineffective arrangement” means average number of hexagonal cells in the arrangements with more usage of electric power.
5.3 Convergence of house agents

As we can see from Fig. 9 to Fig. 12, effective arrangement’s average number of hexagonal cells which contains no agent is more than ineffective arrangement’s. Besides, effective arrangements’ average number of hexagonal cells which contains one or two agents are less than ineffective arrangements’. Thus, when the agents converge, usage of electric power decreases.

Here, let’s focus on the case 1, in which the biggest hexagon is used, and case 4, in which the smallest one is used. The effective arrangement’s average number of hexagonal cells which contains no agents is 7.40, and the ineffective arrangement’s one is 3.10. There is significant difference between them ($t = 7.59, p < 0.01$). Thus, agents in effective arrangement could be more tends to converge than agents in ineffective arrangement.

Furthermore, the effective arrangement which contains 9 agents in one hexagonal consumes least electric power among all arrangements. Thus, when agents with low preset temperature converges, usage of electric power could decreases.

When show the graphs of “number of agents in hexagonal cell” = 0 in Fig. 12, there is significant difference between effective arrangement and ineffective arrangement ($t = 86.80, p \leq 0.01$). Thus, when agents with low preset temperature do not converge, usage of electric power increases.
6 CONCLUSION AND FUTURE WORK

Relationship between arrangements of houses with air-conditioners in an area and the usage of the electric power has been investigated for discovering whether usage of electric power could be changed by altering arrangements of houses. A model of houses with air-conditioner and an outdoor unit has been proposed. Usage of electric power with air-conditioners are simulated by using the proposed model. Specifically, it has been validated that usage of electric power can be reduced through changing arrangements of houses. The following features are discovered from the analysis: If houses with less preset temperature are close with each other, usage of electric power will decrease. If houses with less preset temperature are far from each other, usage of electric power will increase. That is to say, when buildings which have much exhaust heat converge, usage of electric power decreases. This results could contribute for planning of redevelopment of urban areas.

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