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An Energy Distribution Decision Method in Distributed Energy Management Systems with Several Agents

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Abstract: The need to control CO_2 emissions, which are the main factor of global warming, is one of the most important problems in the 21st century. Therefore, the efficient supply and use of energy are indispensable. We have studied distributed energy management systems (DEMSs), in which we target to optimal plans that minimize costs through electrical and thermal energy trading under CO_2 emissions regulation. Previously, a trading method in which the Market Oriented Programming (MOP) is applied to DEMSs was proposed. However, this trading method can be used in the DEMSs consisted of a single consumer and several producers. In this paper, extending this method, we propose a trading method that can be used in DEMSs which consist of several consumers and several producers. Experimental results show that the method is effective in the DEMSs with several consumers and several producers.

Keywords: distributed energy management systems; multi-agent; CO_2 emission; energy trading; the market-oriented programming;

1. INTRODUCTION

Regarding the Earth's environment preservation, the need to control of CO_2 emissions, which are the main factor of global warming, is one of the most important problems in the 21st century. According to the Kyoto Protocol, Japan must reduce its Green House Gas (GHG) emission level by on average 6% with respect to the level measured in 1990 during the period 2008-2012. Due to this obligation, CO_2 emissions regulation might be imposed on each corporation in the future.

If CO_2 emissions regulation is imposed on each corporation, each corporation needs to make efforts to reduce CO_2 emissions, such as introduction of efficient equipment and improvements in efficiency of energy supply. Currently, in Japan, a corporation which has energy generating equipment generates energy only for its energy demand. Recently, deregulation about energy trading enabled corporations to sell energy. For example, about electricity, the customer using more than 50kW could be the candidate of *retail wheeling*. Due to this deregulation, considering the properties of equipment, a corporation may be able to generate energy more efficiently by generating energy beyond its energy demand and selling extra energy. Moreover a corporation may reduce energy consumption by optimization of the operating plan of equipment through energy trading.

We assume a special district (from now on referred as a group) that consists of several independent corporate entities (from now on referred as agents) and in which electrical and thermal energy trading among the agents is allowed. Each agent has electricity and heat demands, and CO_2 emissions regulation is imposed on each agent. We define energy cost of a group as the expenses for energy purchased from outside of the group. We target to obtain optimal plans which minimize the energy cost of the group.

When obtaining optimal plans, it is possible to minimize the group cost using a method, called *whole optimization*, which considers the entire group as one agent. However, the acceptance of the optimal plans by every agent constitutes another problem due to the fact that the optimal plan for the group is not necessarily optimal for each agent. Therefore, we target to reduce group cost by the way that each agent optimize the operating plan of equipment through energy trading which minimizes the energy cost of the agent. We call such multi-agent systems Distributed Energy Management Systems (DEMSs). See Miyamoto et al. [2008].

Considering CO_2 emissions regulation, the mechanism in which CO_2 emissions are imputed from an energy producer to an energy consumer in energy trading is needed. Therefore, we consider not only the unit price but also the CO_2 emission basic unit in energy trading. The CO_2 emission basic unit means the amount of CO_2 emitted by the unit energy consumption.

Previously, a trading method that provides a competitive and balanced plan through the application of the Market Oriented Programming (Wellman [1993]) to DEMSs was

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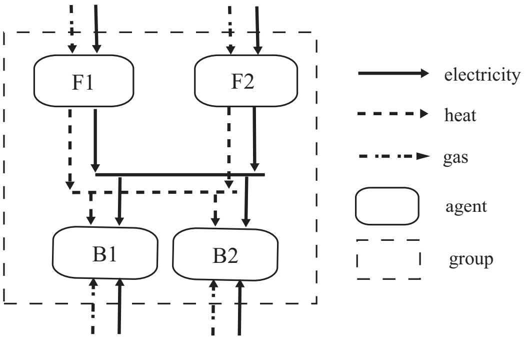

Fig. 1. An example of a group

proposed. See Yakire et al. [2006]. By this method, we succeeded in obtaining a plan close to the plan which is obtained by *whole optimization*. However, this method is only used in a DEMS which consists of a single consumer and several producers. In this paper, extending this method, we propose an energy trading decision method which can be used in a group in which several consumers and several producers exist.

In this paper, first, we describe composition of DEMSs. Then, we propose an energy trading decision method which is used in a group in which several consumers and several producers exist. Finally, we show availability of the proposed method by computational experiments.

2. DISTRIBUTED EMS

A group consists of several autonomous agents. An agent may be an energy consumer/supplier such as a building, a factory, an Independent Power Producer (IPP), and so on. An example of a group configuration is shown in Fig.1. The group consists of two factories F1 and F2, which purchase energy from outside of the group and supply energy to the group, and two buildings B1 and B2, which purchase energy from both agents inside and outside of the group. In the group, agents are connected by power transmission lines and heat pipelines, and they can transmit energy through them. Power transmission lines connect arbitrary agents, and heat pipelines connect particular agents. We do not consider wheeling charge in the group.

Agents are categorized as producers or consumers in the group. In Fig.1, F1 and F2 are producers, and B1 and B2 are consumers. The common features among producers and consumers are as follows:

- Agents have demands for electricity and heat, and the projected demand patterns are given.
- CO_2 emissions regulation is given for each agent.
- The amount of CO_2 emissions is calculated by the difference of CO_2 emissions in the energy purchased by the agent and energy sold by the agent.

Both consumers and producers can purchase energy from outside of the group, but consumers can also purchase energy from inside of the group, and producers can only sell energy to inside of the group. Each agent decides its energy purchase plan and operating plan of equipment that maximizes its own economic profit and that will be subjected to energy demands and CO_2 emissions. An agent cannot be a producer and a consumer concurrently. This means that an agent is not able to purchase and sell energy concurrently in the group. From now on, we will explain technical terms in this paper and agent's strategy which were introduced in our previous study (Yakire et al. [2006]).

Let $\mathcal{P} = \{p_1, \cdots, p_n\}$ represent a set of agents in a group, and n denotes the number of agents in the group. Using $\mathcal{P}$, a set of electricity energies $\mathcal{E}$ is represented as follows: $\mathcal{E} = \{E_{ij}|p_i, p_j \in \mathcal{P}\} \cup \{E_{ei}|p_i \in \mathcal{P}\} \cup \{E_{ie}|p_i \in \mathcal{P}\}$, where, $E_{ij}(t)$ denotes the electricity supply from an agent p_i to an agent p_j at the time t, and $E_{ei}(t)$ denotes the electricity supply from outside of the group to an agent p_i at the time t, $E_{ie}(t)$ denotes the electricity sold from an agent p_i to outside of the group, and t is considered as discrete time. $E_{ij}(t)$ is associated with $(\alpha_{E_{ij}}(t), \beta_{E_{ij}}(t))$, where, $\alpha_{E_{ij}}(t)$ denotes unit price, and $\beta_{E_{ij}}(t)$ denotes the CO_2 emission basic unit. $E_{ei}(t)$ and $E_{ie}(t)$ are also associated with $(\alpha_{E_{ei}}(t), \beta_{E_{ei}}(t))$ and $(\alpha_{E_{ie}}(t), \beta_{E_{ie}}(t))$, respectively. We suppose that the electricity outside of the group is of one kind. This means, $\forall i, j$, $\alpha_{E_{ei}}(t) = \alpha_{E_{ej}}(t)$, $\beta_{E_{ei}}(t) = \beta_{E_{ej}}(t)$, $\alpha_{E_{ie}}(t) = \alpha_{E_{je}}(t)$, and $\beta_{E_{ie}}(t) = \beta_{E_{je}}(t)$.

$\mathcal{H} = \{H_{ij}\}$, $(i, j = 1, \cdots, n, i \neq j)$ denotes a set of heat energies. $H_{ij}(t)$ denotes heat supply from agent p_i to agent p_j at the time t. $H_{ij}(t)$ is associated with $(\alpha_{H_{ij}}(t), \beta_{H_{ij}}(t))$, where $\alpha_{H_{ij}}(t)$ denotes unit price, and $\beta_{H_{ij}}(t)$ denotes the CO_2 emission basic unit.

$\mathcal{K} = \{K_{wi}\}$, $(i = 1, \cdots, n)$ denotes the set of energy resources which are supplied from outside of the group to agent p_i. An example of energy resources is gas. $K_{wi}(t)$ is associated with $(\alpha_{K_{wi}}(t), \beta_{K_{wi}}(t))$.

$\mathbb{R}^+$ denotes the set of non-negative real numbers. The amount of $E \in \mathcal{E}$ traded at the time t is expressed by the function $Q(t, \mathcal{E}) : \mathcal{E} \rightarrow \mathbb{R}^+$, where the following constraints on $BE_i(t)$ and $SE_i(t)$ must be hold:

$$BE_i(t) = \sum_{j \neq i \vee j = e} Q(t, E_{ji}), \text{and} \tag{1}$$

$$SE_i(t) = \sum_{j \neq i \vee j = e} Q(t, E_{ij}). \tag{2}$$

The amount of $H \in \mathcal{H}$ traded at the time t is expressed by the function $R(t, \mathcal{H}) : \mathcal{H} \rightarrow \mathbb{R}^+$, where, the following constraints on $BH_i(t)$ and $SH_i(t)$ must be hold:

$$BH_i(t) = \sum_{j \neq i} R(t, H_{ji}), \text{and} \tag{3}$$

$$SH_i(t) = \sum_{j \neq i} R(t, H_{ij}). \tag{4}$$

The cost of agent p_i at the time t is expressed as follows:

$$\begin{aligned} J_i(t) = X_i(t) &+ \sum_{j\neq i \vee j=e} \alpha_{E_{ji}}(t)\cdot Q(t,E_{ji}) \\ &+ \sum_{j\neq i} \alpha_{H_{ji}}(t)\cdot R(t,H_{ji}) \\ &+ \sum_{K_{wi}\in\mathcal{K}} \alpha_{K_{wi}}(t)\cdot WK_{wi}(t) \\ &- \sum_{j\neq i \vee j=e} \alpha_{E_{ij}}(t)\cdot Q(t,E_{ij}) \\ &- \sum_{j\neq i} \alpha_{H_{ij}}(t)\cdot R(t,H_{ij}), \end{aligned} \tag{5}$$

where, $X_i(t)$ denotes costs except for the cost for energy trading, for example, a cost which is needed when an agent starts or stops it's equipment.

In this paper, we consider CO_2 only emitted from energy consumption (purchase). The amount of CO_2 emissions of agent p_i at the time t is given as follows:

$$\begin{aligned} CO_{2i}(t) = &\sum_{j\neq i \vee j=e} \beta_{E_{ji}}(t)\cdot Q(t,E_{ji}) \\ &+ \sum_{j\neq i} \beta_{H_{ji}}(t)\cdot R(t,H_{ji}) \\ &+ \sum_{K_{wi}\in\mathcal{K}} \beta_{K_{wi}}(t)\cdot WK_{wi}(t) \\ &- \sum_{j\neq i \vee j=e} \beta_{E_{ij}}(t)\cdot Q(t,E_{ij}) \\ &- \sum_{j\neq i} \beta_{H_{ij}}(t)\cdot R(t,H_{ij}). \end{aligned} \tag{6}$$

The condition on the CO_2 emissions of agent p_i is given by:

$$\sum_{t\in T} CO_{2i}(t) \leq K_i(T), \tag{7}$$

where, $K_i(T)$ denotes CO_2 emissions cap of agent p_i for period T.

Let $\mathcal{U}_i = \{u_1, \cdots, u_m\}$ denote the set of equipments of agent p_i. Let IE_k denote the amount of input electricity to the equipment u_k, IH_k denote the amount of input heat to the equipment u_k, IK_{wik} denote the amount of input energy K_{wi} to the equipment u_k, OE_k denote the amount of output electricity from the equipment u_k, and OH_k denote the output heat from the equipment u_k. Then input-output function of each equipment is expressed by a function $\Gamma_k : \mathbb{R}^{+\{IE_k(t), IH_k(t), IK_{wik}(t)\}} \to \mathbb{R}^{+\{OE_k(t), OH_k(t)\}}$. For example, Γ_k of equipment which have one energy input and several energy outputs, such as gas boilers and gas turbines, is given by:

$$O_l(t) = p_l I^{b_l}(t) - d_l, (l = 1, \cdots, m), \tag{8}$$

where, m denotes the numbers of output energies, I denotes the amount of input energy, and O_l denotes the amount of output energy l. p_l, d_l and b_l are constants, and $p_l, d_l > 0$, $0 < b_l < 1$.

Electricity balance equation in an agent is described as follows:

$$\begin{aligned} &BE_i(t) + \sum_{k=1}^{m} OE_k(t) = \\ &\qquad DE_i(t) + SE_i(t) + \sum_{k=i}^{m} IE_k(t), \end{aligned} \tag{9}$$

where, DE_i denotes the amount of demand for electricity.

Heat balance equation in an agent is described as follows:

$$\begin{aligned} &BH_i(t) + \sum_{k=1}^{m} OH_k(t) = \\ &\qquad DH_i(t) + SH_i(t) + WH_i(t) + \sum_{k=i}^{m} IH_k(t), \end{aligned} \tag{10}$$

where, DH_i denotes the amount of demand for heat, WH_i denotes the amount of waste of heat.

A balance equation of other energy K_{wi} is described as follows:

$$BK_{wi}(t) = \sum_{k=i}^{m} IK_{wik}(t), \tag{11}$$

where, BK_{wi} denotes the amount of purchased energy K_{wi}.

Decision of agent p_i is made by solving the planning problem as follows:

$$\min \sum_{t\in T} J_i(t) \tag{12}$$

$$\text{s.t. } \forall t \in T :$$

$$(1) - (11) \tag{13}$$

$$\forall u_k \in \mathcal{U}_i : \Gamma_k \tag{14}$$

If we consider multi-period optimization, we need to solve a combinational optimization problem due to the costs that are needed when equipment is started or stopped. In this paper, we consider single period optimization. This means that we assume that $|T| = 1$.

At the following, we show two examples of agents which are called building and factory respectively, and show the plannnig problems of the agents.

Building model

Let a building have a gas boiler and no electricity generators. The building is able to produce heat by purchasing gas. The building model is shown in Fig.2. In the figure, BE_e denotes the amount of electricity supply from outside of the group, BE denotes the amount of electricity supply from inside of the group, BH denotes the amount of heat supply from inside of the group, BG denotes the amount of gas supply from outside of the group, BA denotes a gas boiler, PH denotes the amount of heat generated by the BA, DE denotes the amount of electricity demand, DH denotes the amount of heat demand.

The planning problem for the building is described as follows.

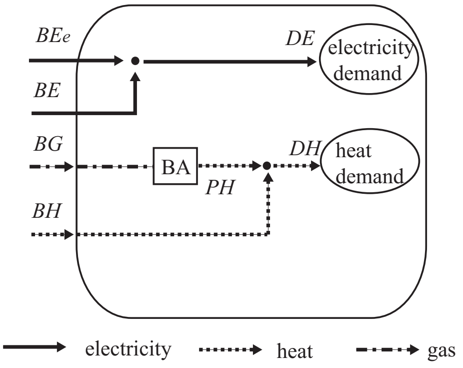

Fig. 2. A building model

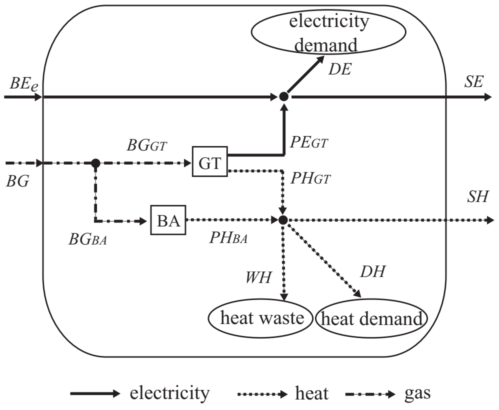

Fig. 3. A factory model

$$
\begin{aligned}
\min\ & \alpha_{BE_e}BE_e+\alpha_{BE}BE+\alpha_{BG}BG+\alpha_{BH}BH \\
\text{s.t. } & PH = p_{BA}BG^{b_{BA}} - d_{BA} \\
& BE_e + BE = DE \\
& BH + PH = DH \\
& \beta_{BE_e}BE_e+\beta_{BE}BE+\beta_{BG}BG+\beta_{BH}BH\leq K
\end{aligned}
$$

Factory model

Let a factory have a gas turbine and a gas boiler. The factory can produce electricity and heat by purchasing gas. The factory model is shown in Fig.3. In the figure, GT denotes a gas turbine, PE_{GT} denotes the amount of electricity generated by the GT, PH_{GT} denotes the amount of heat generated by the GT, SE denotes the amount of electricity supply to inside of the group, SH denotes the amount of heat supply to inside of the group. WH denotes the amount of heat waste.

The planning problem for factory is described as follows:

$$
\begin{aligned}
\min\ & \alpha_{BE_e}BE_e + \alpha_{BG}BG - \alpha_{SE}SE - \alpha_{SH}SH \\
\text{s.t. } & PE_{GT} = p_{GT_E}BG_{GT}^{b_{GT_E}} - d_{GT_E} \\
& PH_{GT} = p_{GT_H}BG_{GT}^{b_{GT_H}} - d_{GT_H} \\
& PH_{BA} = p_{BA}BG_{BA}^{b_{BA}} - d_{BA} \\
& BE_e + PE_{GT} = DE + SE \\
& PH_{GT} + PH_{BA} = DH + SH + WH \\
& BG = BG_{GT} + BG_{BA} \\
& \beta_{BE_e}BE_e+\beta_{BG}BG-\beta_{SE}SE-\beta_{SH}SH \leq K
\end{aligned}
$$

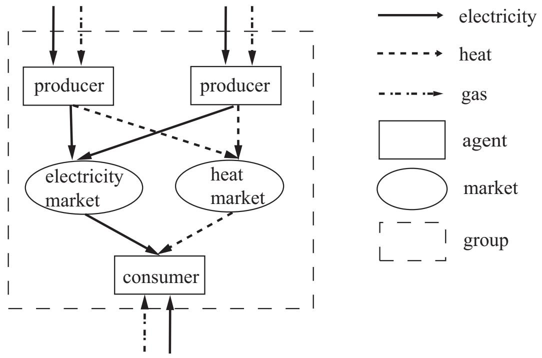

Fig. 4. Markets in the group with single consumer

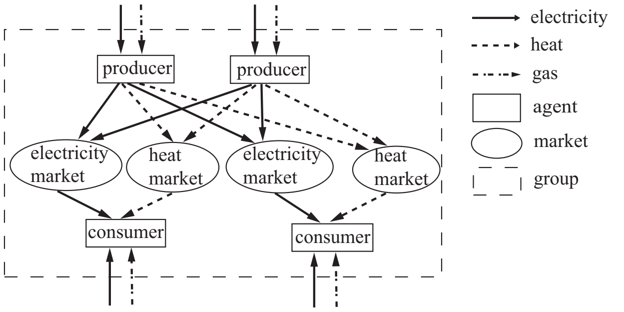

Fig. 5. Markets in the group with multiple consumers

3. ENERGY TRADING DECISION METHOD IN A GROUP WITH SEVERAL CONSUMERS

3.1 A trading method for DEMS with several consumers

In our previous method (Yakire et al. [2006]), a consumer establishes markets for both electricity and heat energy and all producers participate in the markets as shown in Fig.4. Then the amounts of energy traded in the two markets are determined by the MOP. Note that the CO_2 emission basic unit of traded energy in each market is fixed to the value desired by the consumer.

There are two methods that can be used in a group in which several consumers and several producers exist. One is the method in which all consumers and producers trade energy in only one electricity market and one heat market established in the group. The other is the method in which each consumer establishes markets for electricity and heat energy, and all producers take part in their markets as shown in Fig.5. The former cannot be used in a situation in which each consumer desires different CO_2 emission basic unit. However, the latter can be used in such a situation by fixing the CO_2 emission basic unit in each market to the value desired by the consumer. Therefore, we use the latter.

3.2 Modification of the objective function

In our previous work, equation (5) is used for the objective function. However, if we use (5) in DEMSs with several consumers, a problem concerning the convergence to a state of competitive equilibrium arises. Fig.6 shows changes in the amounts of demand and supply bids in a particular electricity market. The vertical axis represents the amount of agents' bids for electricity and the horizontal

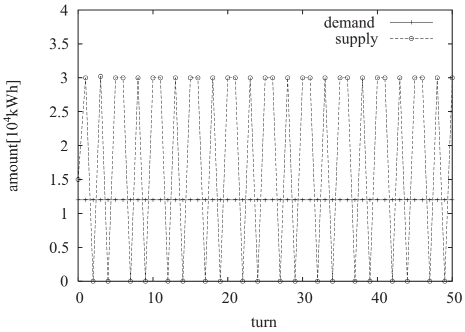

Fig. 6. Bids in electricity market of Building1

axis represents the turn in which these bids occurred. The term "turn" denotes a point in time which the following process occurs: First, each market presents a price for the traded energy. Then the consumers, based on the markets' prices, decide the demand bid for the traded energy, and the producers decide the supply offer to the market. Finally, each market adjusts its price according to the difference between the demand and the supply of the traded energy. This process is repeated until the demand and the supply values become equal in all markets. This condition is called competitive equilibrium. As shown in Fig.6, the amount of supply bids continues to vary, the bidding system is not able to converge to a state of competitive equilibrium. This is caused by the attempt of producers to supply electricity (heat) only to the electricity (heat) market which presents the highest price in each turn. Therefore, we change the agent's objective function as follows:

$$\begin{aligned} J_i(t) = X_i(t) + &\sum_{j \neq i \vee j = e} \alpha_{E_{ji}}(t) \cdot Q(t, E_{ji}) \\ &+ \sum_{j \neq i} \alpha_{H_{ji}}(t) \cdot R(t, H_{ji}) \\ &+ \sum_{K_{wi} \in \mathcal{K}} \alpha_{K_{wi}}(t) \cdot WK_{wi}(t) \\ &- \sum_{j \neq i \vee j = e} \alpha_{E_{ij}}(t) \cdot k \ln\left(\frac{1}{k} Q(t, E_{ij}) + 1\right) \\ &- \sum_{j \neq i} \alpha_{H_{ij}}(t) \cdot k \ln\left(\frac{1}{k} R(t, H_{ij}) + 1\right) \qquad (15) \end{aligned}$$

As shown in (15), we change the functions which denote an agent's incomes, obtained by supply of energy to a market, from linear functions to logarithmic functions. The constant k is related to the slope of the logarithmic functions. If we increase k, the logarithmic functions are close to the linear functions we had in the previous objective function. The slopes of logarithmic functions are monotonically decreasing. That is to say, the more amount of energy a producer tries to supply to one market, the lower increase in the rate of the utility from the supply he obtains. Due to this characteristics, a producer will supply energy not only to the market presenting the highest price but also to the other markets. The effects of (15) is shown in next section.

Table 1. Parameters of energy outside the group

α_{BE_e}(yen/kWh)	10.39
β_{BE_e}(kg-CO$_2$/kWh)	0.317
α_{BG}(yen/m^3)	28.6
β_{BG}(kg-CO$_2$/m^3)	1.991

Table 2. Parameters of the agents

	B1	B2	F1	F2
DE(kWh)	12000	6000	40000	20000
DH(Mcal)	60000	55000	30000	15000
K(kg-CO$_2$)	30000	30000	30000	30000
p_{BA}(Mcal/m^3)	35.03	31.85	37.22	37.02
b_{BA}	0.85	0.85	0.85	0.85
Capacities of gas boilers(Mcal)	60000	55000	10000	5000
p_{GT_E}(kWh/m^3)	-	-	17.92	16.32
b_{GT_E}	-	-	0.85	0.85
Capacities of gas turbines(kWh)	-	-	50000	30000
p_{GT_H}(Mcal/m^3)	-	-	31.85	25.88
b_{GT_H}	-	-	0.85	0.85

4. COMPUTATIONAL EXPERIMENT

In this section, we present two experiments, the first is aimed to confirm that competitive equilibrium could be obtained by the proposed method, the second is aimed to investigate the effects of the change of k. The two experiments are performed under the same following conditions: the group consists of two consumers B1, B2 and two producers F1, F2, as shown in Fig.1. F1 and F2 have the same structure as shown in Fig.3. Similarly, the structure of B1 and B2 is the same as shown in Fig.2. Price per unit and the CO$_2$ emission basic unit of energy from outside of the group are shown in Table 1. The agents' parameters are shown in Table 2.

4.1 convergence evaluation of the proposed method

This experiment is aimed to confirm that competitive equilibrium could be obtained by the proposed method. We fixed the value of k to 10^5. The experimental results are shown in Fig.7, 8, and Table 3, 4. These figures shows that the bidding system converged to a state of competitive equilibrium by proposed method. This happens because producers try to supply electricity to the market which presents the lower price of the two electricity markets. As in the electricity markets, in each heat market, the amount of demand and of supply converge to the competitive equilibrium. Table 3 shows the energy trading amounts obtained in this experiment. Table 4 shows the comparison between cost of the group obtained by the proposed method and the ones obtained by other methods. Cost of an agent is calculated from (12), and cost of the group is calculated from sum of all the agents' cost. In Table 4, *single optimization* means that each agent minimize their cost without electricity and heat trading in the group. cost obtained by *whole optimization* is lower bound for the group. Table 4 also shows that the cost of the group obtained by the proposed method is smaller than the cost obtained by single optimization, and is closer to the cost obtained by whole optimization. Therefore, we succeed to obtain near optimal solution by the proposed method.

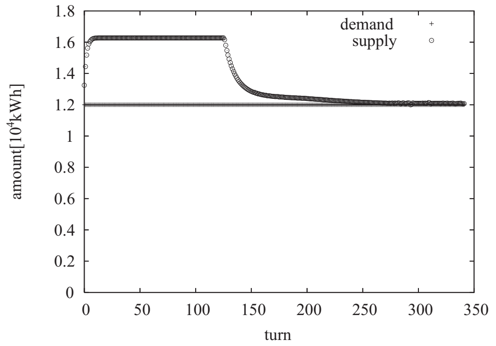

Fig. 7. Bids in electricity market of Building1

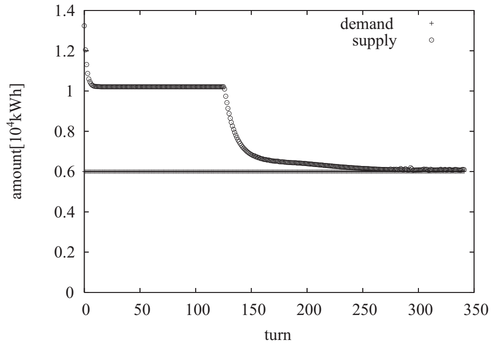

Fig. 8. Bids in electricity market of Building2

Table 3. Amount of trading

consumer	energy	price	Supply from F1	Supply from F2
B1	electricity	4.468	6931	5150
	heat	2.727	34174	17758
B2	electricity	4.342	3912	2183
	heat	2.738	34679	18203

Table 4. Comparison of cost

	B1	B2	F1	F2	group
single optimization	324933	266222	309349	184832	1085336
proposed method	225574	187421	156243	110967	680205
whole optimization					676819

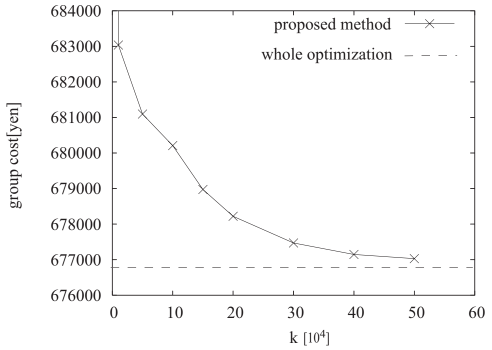

Fig. 9. Change of group cost according to change of k

4.2 evaluation of effects of the constant in the proposed objective function

This experiment is aimed to investigate effects of k in (15). The result is shown in Fig.9. The horizontal axis is k, and the vertical axis is cost of the group obtained by the proposed method. As shown in Fig.9, the larger the value of k becomes, the closer the group cost value obtained by the proposed method becomes to the one obtained by *whole optimization*. Furthermore, if the value of k exceeds about 600000, the problem that the proposed method does not converge to a state of competitive equilibrium arises as shown in Fig.6. This is due to (15) becoming closer to (5) with the increase in the value of k. A producer's objective in energy trading is closer to the minimization of the producer's cost by increase in the value of k. Therefore, a cost of the group become smaller as a result of the increase in the value of k. However, the convergence problem will occur as k increases to extremely large values.

If we change the experimental condition (that is structure of the group, and agents' parameters), the maximum value of k at which the proposed method can converge to competitive equilibrium also changes. Therefore, if we try to minimize the cost obtained by the proposed method, we need to adjust the value of k in each condition. This problem is an issue for the future.

5. CONCLUSION

In this paper, we studied the application of the MOP to DEMSs where the group consists of several consumers and several producers. We propose the objective function of which the slope is monotonically decreasing. In the computational experiment, we confirm that the bidding system converge to a state of competitive equilibrium by the proposed method, and we confirm the optimality of the cost which is obtained by the proposed method. Therefore, we confirm that the application of the MOP to DEMSs with several consumers is effective. The comparison of the proposed objective function with other objective functions is also an issue for the future.

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