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Potential to reduce energy consumption by establishing distributed energy system in the exiting office and apartment buildings

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ABSTRACT

Recently, the reduction of CO_2 emission is required for all of individual stakeholders, such as constructors, building owners and occupants in building sector. One of the strategies, which are expected immediate results, is to establish “distributed energy systems” which share the energy among the buildings. To promote the distributed energy systems effectively, quantitative design method is needed. The authors have already developed and proposed a new optimized design method for building energy systems or distributed energy systems using genetic algorithms (GA) in some previous studies [1]. This method leads to the optimal solution in terms of combination and its operation in order to minimize primary energy consumption. In this research, optimization for existing office and apartment buildings is calculated using the GA method. In optimization cases for individual buildings, offices and apartments, each has the potential to reduce the primary energy consumption beyond that designed by professional engineers. If distributed energy systems were established among office and apartment buildings, it is expected that primary energy consumption could be further reduced.

Keywords
Distributed energy system, Existing building, Cogeneration, Machinery behaviour, Optimization

INTRODUCTION

Distributed energy systems

Distributed energy systems based on cogeneration systems afford excellent energy-saving potential through the effective use of waste heat from power generators. However, unless an appropriate combination of machinery and operation is used, the potential performance is not achieved, but it is quite difficult to determine the optimal combination of machinery and operation. Some practical designs concerning distributed energy systems are constructed based on experimental results by professional system engineers. However, in order to promote the concept of distributed energy systems, a quantitative design method is needed.

Optimal design method

With regard to optimal design methods for energy systems, some researchers have already developed and proposed methods applying some optimization techniques. One based on linear programming (LP) was established by Ito [2], but it is difficult to examine applications for recent machinery with nonlinear characteristics using LP. Bearing this in mind, Huang [3] applied GA to the optimization of HVAC control parameters, Obara [4] used GA for operational optimization of complex energy systems, and D.A. Manolas [5] proposed using GA. However, their methods were established for specific energy systems, which have their own machinery combinations, and whose capacities are already known.

The authors had already developed and proposed a new optimal design method for building energy systems or distributed energy systems using genetic algorithms (GA) in some previous studies [1]. GAs are able to handle nonlinear optimization problems. The proposed method designs the most efficient energy system by optimizing operation of available systems with consideration for the optimal machinery capacity in the systems. In this part, in order to calculate the optimal operation for each type of machinery, output is divided into 11 steps at 10-percent intervals, namely 0, 10, 20, … 90, 100%.

METHODS

Energy system modeling

In order to calculate the energy consumption of a system, the system model is composed of three elements: fuel resources, system machinery, and energy demand. Figure 1 shows the correlation between elements. There are three types of fuel resource: city gas, electricity, and solar energy. There are four types of energy demand: cooling demand (CD), heating demand (HD), hot water demand (WD), and electricity demand (ED). Table 1 shows the machinery lineup for the energy system model. Each item of machinery has its own characteristics, fuel resource and possible supply.

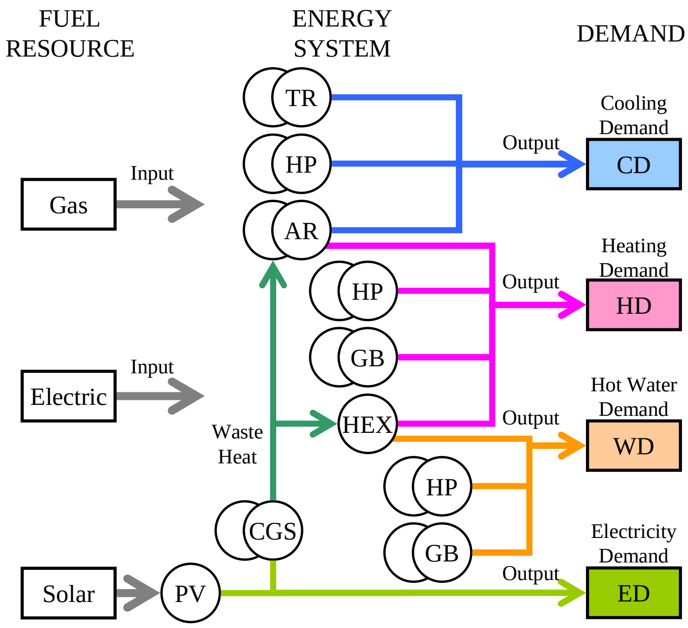

Figure 1. Energy System Modeling

Table 1. Machinery List

		COP		Input		Output			
		C	H	Gas	Elec	C	H	W	E
AR	Absorption Refrigerator	1.1	0.8	●		●	●		
TR	Turbo Refrigerator	2.5	---		●	●			
HP	Electrical Heat Pump System	1.4	1.4		●	●	●	●	
GB	Gas Boiler	---	0.9	●			●	●	
CGS	Co-Generation System	0.36*1		●		○	○	○	●
PV	Photovoltaic Power System	---							●

C: Cool Output H: Hot Output W: Hot Water E: Electricity

○ : output as waste heat

COP: Coefficient of Performance (=Output/Input)

※COP value of this study is based on catalogue information.

*1 : COP for generation only (does not include waste heat efficiency)

Chromosome coding

Figure 2 indicates the information coding for the chromosomes. The chromosomes have 20 cells relating to their output form. In order to exam machinery division, each machine has two cells. The seventh, 12th, and 17th sets of information are about the fuel type, namely heat pump (HP), electricity or gas. Information concerning the Photovoltaic Power System (PV) is described in square meters [m^2] based on its coverage area.

	1	2	3	4	5	6	7	8	9	10	11	12
source	Cooling							Heating				
name	TR1	TR2	HPc1	HPc2	AR1	AR2	eneHP	GBh1	GBh2	HPh1	HPh2	eneHP
unit	RT	RT	HP	HP	RT	RT	G/E	kW	kW	HP	HP	G/E

	13	14	15	16	17	18	19	20
	Hot Water					Electricity		
……	GBw1	GBw2	HPw1	HPw2	eneHP	CGS1	CGS2	PV
	kW	kW	HP	HP	G/E	kW	kW	m^2

Figure 2. Chromosome Coding

Energy demand

Energy demand data is one of the important parameter to detect optimal energy system in terms of simulation. In the process of energy system design, demand data can be prepared by the results of heat load calculation, or investigated values from existing buildings. Each article of demand data is classified as [kW/m^2] or [kWh/m^2]. In order to use the value in the calculation, representative data for each season was selected. An August day represents summer demand, an April day as mid-season demand, and a January day as winter demand. 24 hours of a representative day of each month is set as the input data for the calculation. The demand data in this research is prepared for existing buildings in Tokyo.

Machinery data

Figure 3 shows the machinery performance curve such as for the Absorption Refrigerator (AR), Turbo Refrigerator (TR), Heat Pump system (HP), and Gas Boiler (GB). The characteristic curve becomes a non-linear function of the machine load rate except for the GB. Machinery efficiency is defined as the performance fuel consumption rate. Because of the high driving control technology with the inverter that has been developed, the machinery characteristic has a non-linear energy input and output power characteristic. The optimization technique where GA is applied can be described as effective where the machinery characteristics are strongly dependent on the machinery capacity or load factor.

The machinery data referred to is the manufacturer's catalogue value and the value of the machinery database of the CEC/AC calculation program "BECS/CEC/AC for Windows" published by the Institute for Building Environment and Energy Conservation (IBEC) based on the energy-saving method [6]. The machinery capacity in co-generation systems (CGS) is based on the manufacturer's catalogue value, so a fixed value of 45.6% for generating efficiency and 31.4% for exhaust heat efficiency is assumed for calculation purposes. The fuel consumption efficiency referred to is calculated from the AR information. The generation efficiency of the commercial electricity assumes 52.8% (efficiency of generator edge) for the 1,500 degree more advanced combined-cycle (MACC) generator.

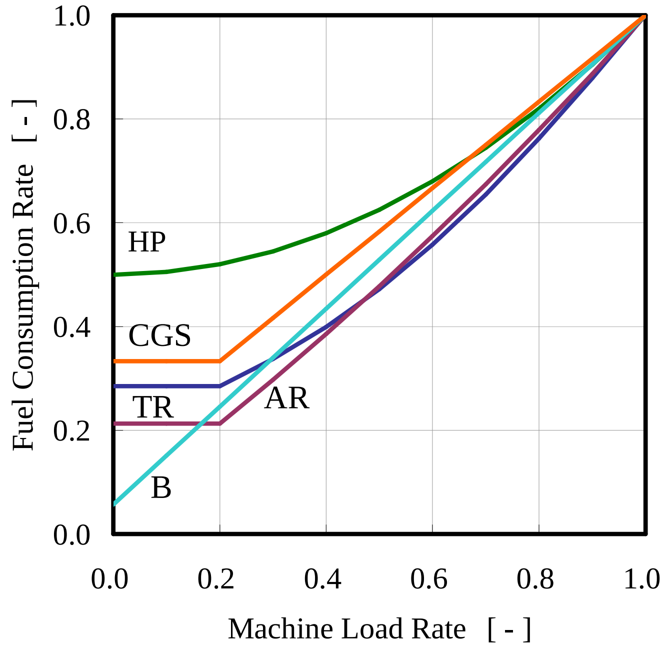

Figure 3. Machinery Performance

CASE STUDY

In this research, optimization for existing office and apartment buildings are calculated using the GA method. We calculated eight cases for individual energy systems and three cases for distributed energy systems. The main objective of this research is to estimate the optimal heat balance among existing buildings.

Building profile

The office building (15,800 m^2) has a large cooling demand in summer, small cooling demand mid-season, and doesn't have hot water demand throughout the year. On the other hand, the apartment building (33,600 m^2) has constant hot water demand throughout the year. Related to cooling demand of the apartment building, these are counted in terms of electrical demand, because each building unit has heat-pump air conditioners in each room.

Individual building cases

Cases 1-0 and 2-0 are set as designed manually. This means their results are not optimized using our method, but rather have been determined by the building system experts based on their experience. Cases 1-1 and 2-1 are optimized only in terms of their operations with the same machinery combinations as Cases 1-0 and 2-0 in order to compare the effect of operational optimization. Cases 1-2 and 2-2 involve GA optimization of machinery combinations including CGS. On the other hand, Cases 1-3 and 2-3 also involve GA optimizations, but exclude CGS in order to compare the effect of waste heat utilization from CGS. All of these cases concern an individual building. The results of Cases 1-0 and 2-0 are referenced by the results reported by R. Kuzuki [7].

Two-building connection cases

Cases 1-a and 2-a concern individual optimizations equivalent to the results of Cases 1-2 and 2-2. Cases 1-b and 2-b are operationally optimized when two buildings are connected in order to compare the effect of building connection. Moreover, Cases 1-c and 2-c are GA optimized to including two complete buildings. All comparisons are presented in Table 2.

Table 2. Case scenarios

CASES	COMBINATION	OPERATION	ENERGY SYSTEM	REMARKS
Case 1-0	Design by manual	Design by manual	Office (individual)	Design by manual
Case 1-1	Design by manual	Optimization	Office (individual)	Optimization only operation
Case 1-2	GA optimization	Optimization	Office (individual)	GA optimization (inc CGS)
Case 1-3	GA optimization	Optimization	Office (individual)	GA optimization (exc CGS)
Case 2-0	Design by manual	Design by manual	Apartment (individual)	Design by manual
Case 2-1	Design by manual	Optimization	Apartment (individual)	Optimization only operation
Case 2-2	GA optimization	Optimization	Apartment (individual)	GA optimization (inc CGS)
Case 2-3	GA optimization	Optimization	Apartment (individual)	GA optimization (exc CGS)
Case 1-a	GA optimization	Optimization	Office (individual)	Individual optimization (= Case1-2)
Case 1-b	Combination of Case1-a	Optimization	Office (connected)	Optimization only operation when 2 buildings are connected
Case 1-c	GA optimization	Optimization	Office (connected)	GA Optimization including 2 buildings
Case 2-a	GA optimization	Optimization	Apartment (individual)	Individual optimization (= Case2-2)
Case 2-b	Combination of Case2-a	Optimization	Apartment (connected)	Optimization only operation when 2 buildings are connected
Case 2-c	GA optimization	Optimization	Apartment (connected)	GA Optimization including 2 buildings

Objective

The objective (F_{total}) of this case study was to minimize primary energy consumption [MJ/3 days]. F_{total} is defined by the following Equation (1).

$$F_{total} = objQ_{win} + objQ_{mid} + objQ_{sum} \qquad (1)$$

where $objQ_{win}$ is the primary energy consumption on a representative day in winter [MJ/day], $objQ_{mid}$ is the primary energy consumption on a representative day mid-season [MJ/day], and $objQ_{sum}$ is the primary energy consumption on a representative day in summer [MJ/day]. The boundaries of the energy system were only coolers and heaters in order to simplify the optimization problem. Table 2 shows the design variables. Design variables included two ARs, two TRs, HPs for cooling and heating, and a GB for heating. Each variable has five capacity levels, starting from zero. Capacity zero means that the system candidate does not include such machinery.

Design variables

Table 3 shows the selection range for each variable. The variables are not continuous, but step changes based on the machinery lineup. Basically kilowatts are used as the unit in the calculation model. Some machinery that can supply both cool and hot output uses other units, such as RT for AR, or HP for HP. In the calculation, RT or HP is converted into kW of the relevant supply.

Table 3. Design variables

Cooling				Cooling/ Heating		Heating				Hot Water				Electricity		
TR1	TR2	HP1	HP2	AR1	AR2	GB1	GB2	HP1	HP2	GB1	GB2	HP1	HP2	CGS1	CGS2	PV1
[RT]	[RT]	[HP]	[HP]	[RT]	[RT]	[kW]	[kW]	[HP]	[HP]	[kW]	[kW]	[HP]	[HP]	[kW]	[kW]	[m2]
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
125	125	10	10	40	40	58	58	10	10	58	58	10	10	115	115	50
150	150	13	13	50	50	87	87	13	13	87	87	13	13	200	200	100
200	200	16	16	100	100	116	116	16	16	116	116	16	16	230	230	250
215	215	20	20	120	120	151	151	20	20	151	151	20	20	300	300	500
250	250	25	25	180	180	186	186	25	25	186	186	25	25	350	350	750
300	300	32	32	250	250	232	232	32	32	232	232	32	32	480	480	1,000

Pipeline among building

When two-building connection cases are calculated, transferring heat loss and energy consumption using heat-transfer pumps is considered depending on the length of the pipeline. Heat transferal is available when one building has enough waste heat and another building cannot meet all its heating requirements from its own waste heat. Also, if one building has no form of demand at that time, and another building has some kind of heat demand, machinery can supply for the other building’s demands. Four kinds of heat-transfer pipeline are proposed, cold water, hot water at low and high temperatures, and steam.

RESULTS

Individual building cases

Table 4 shows the results of machinery combinations in individual cases. The calculation results show that the GA optimization cases (Cases 1-2 and 2-2) led to a smaller objective, and include more machinery than the manual design (Cases 1-0 and 2-0). This demonstrates that a variety of machinery capacities is able to response to demand changes in detail.

Figure 4 presents a comparison of primary energy consumption on representative days in three different seasons. Operation optimization cases (Cases 1-1 and 2-1) consume less primary energy compared with those designed manually (Cases 1-0 and 2-0). Cases that optimize both the machinery combinations and their operation (Cases 1-3 and 2-3) reduce primary energy consumption. Moreover, comparison of GA optimization cases including CGS (Cases 1-2 and 2-2) and those excluding CGS (Cases 1-3 and 2-3) show that waste heat can be utilized.

Table 4. Result of machinery combinations (individual cases)

		Cooling				Cooling/Heating		Heating				Hot Water				Electricity		
		TR1 [RT]	TR2 [RT]	HP1 [HP]	HP2 [HP]	AR1 [RT]	AR2 [RT]	GB1 [kW]	GB2 [kW]	HP1 [HP]	HP2 [HP]	GB1 [kW]	GB2 [kW]	HP1 [HP]	HP2 [HP]	CGS1 [kW]	CGS2 [kW]	PV1 [m2]
OFC	Case 1-0 Case 1-1	*0*	*0*	*0*	*0*	*180*	*180*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
	Case 1-2	*300*	*0*	*10*	*0*	*180*	*50*	*58*	*0*	*32*	*0*	*0*	*0*	*0*	*0*	*350*	*0*	*1,000*
	Case 1-3	*125*	*250*	*8*	*13*	—	—	—	—	*40*	*10*	—	—	*0*	*0*	—	—	*1,000*
APT	Case 2-0 Case 2-1	*0*	*0*	*0*	*0*	*0*	*0*	*186*	*186*	*0*	*0*	*116*	*116*	*0*	*0*	*0*	*0*	*0*
	Case 2-2	*0*	*0*	*0*	*0*	*0*	*0*	*58*	*0*	*32*	*0*	*58*	*232*	*13*	*20*	*350*	*0*	*1,000*
	Case 2-3	*0*	*0*	*0*	*0*	—	—	—	—	*40*	*10*	—	—	*100*	*50*	—	—	*1,000*

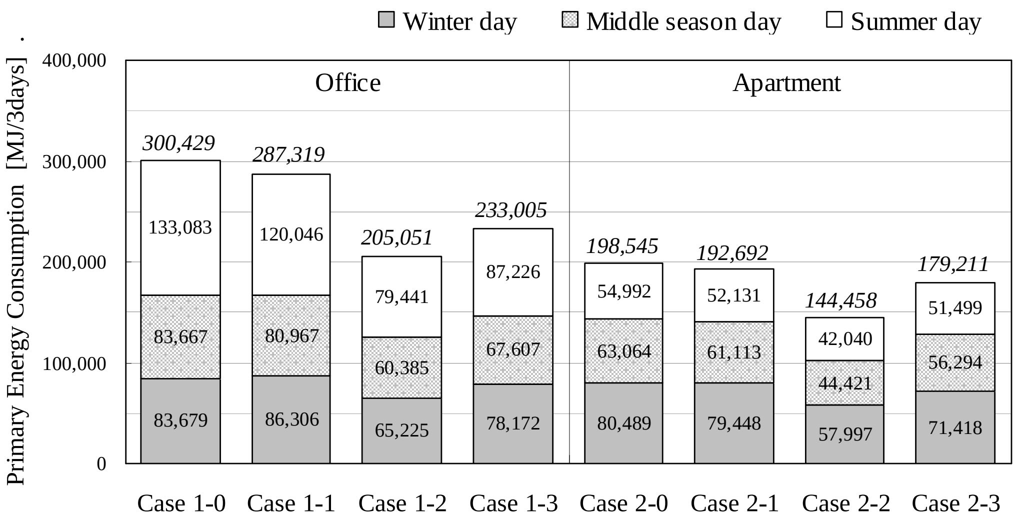

Figure 4. Comparison of primary energy consumption

Two-building connection cases

Table 5 shows the result of machinery combinations in two-building connection cases. Both Cases 1-a and 2-a are the results from Cases 1-1 and 2-2. These cases are selected in order to estimate the effect of sharing heat among buildings. If the two buildings were connected by a pipeline (Cases 1-b and 2-b), energy consumption could be reduced by an estimated 6.3% in the office, and 3.2% in the apartment building. Moreover, if machinery combinations in each energy system were optimized (Cases 1-c and 2-c), energy consumption could be reduced by an estimated 1.1% in the office, and 1.3% in the apartment building. Compared with Cases 1-a and 1-c, a 7.4% reduction in energy consumption is estimated. Correspondingly, 4.5% of that is estimated to be reduced in comparison to Cases 2-a and 2-c. These results demonstrate that distributed energy systems have the potential to reduce energy consumption.

Waste heat can be transferred from office to apartment buildings in the mid-season. CGS in the office building works based on its large electrical demand, and the limited cooling demand cannot use all of the waste heat from the CGS. On the other hand, the apartment building lacks waste heat because the electricity demand is not so large, despite the demand for hot water and heating. In summer, waste heat can be transferred in the reverse direction. Apartment buildings have limited hot water and electrical demands, whereas office buildings have huge cooling and electrical demands. Surplus waste heat from the apartment building can be transferred to the office building. Therefore, utilization of waste heat from the office building reduces primary energy consumption.

Table 5. Result of machinery combination (building connection cases)

		Cooling				Cooling/Heating		Heating				Hot Water				Electricity		
		TR1	TR2	HP1	HP2	AR1	AR2	GB1	GB2	HP1	HP2	GB1	GB2	HP1	HP2	CGS1	CGS2	PV1
		[RT]	[RT]	[HP]	[HP]	[RT]	[RT]	[kW]	[kW]	[HP]	[HP]	[kW]	[kW]	[HP]	[HP]	[kW]	[kW]	[m2]
OFC	Case 1-a Case 1-b	*300*	*0*	*10*	*0*	*180*	*50*	*58*	*0*	*32*	*0*	*0*	*0*	*0*	*0*	*350*	*0*	*1,000*
	Case 1-c	*300*	*0*	*32*	*0*	*100*	*0*	*58*	*0*	*32*	*0*	*0*	*0*	*0*	*0*	*350*	*0*	*1,000*
APT	Case 2-a Case 2-b	*0*	*0*	*0*	*0*	*0*	*0*	*58*	*0*	*32*	*0*	*58*	*232*	*13*	*20*	*350*	*0*	*1,000*
	Case 2-c	*0*	*0*	*0*	*0*	*0*	*0*	*87*	*0*	*25*	*0*	*186*	*116*	*13*	*20*	*350*	*0*	*1,000*

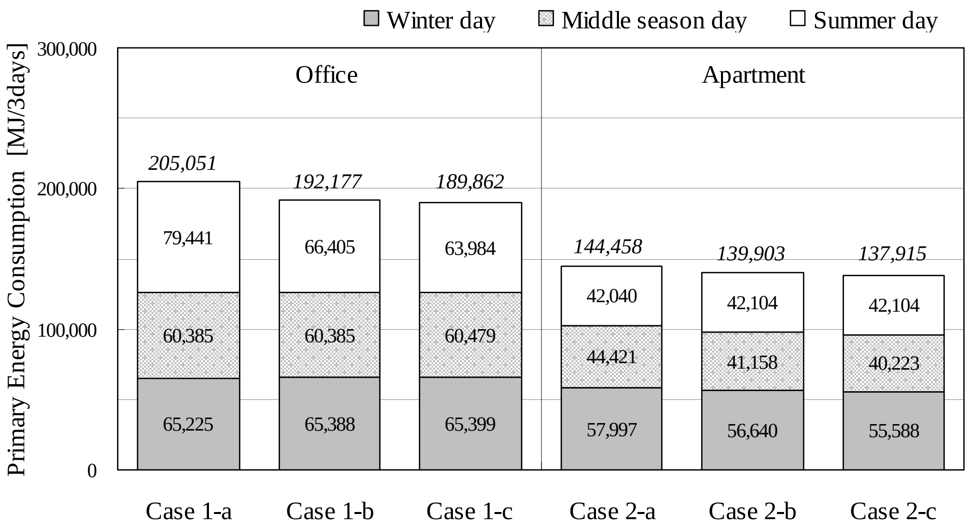

Figure 5. Comparison of primary energy consumption

DISCUSSION

In this research, optimization for existing office and apartment buildings was calculated using the GA method. We calculated eight cases regarding individual energy systems and three cases for distributed energy systems. The main objective of this research is to estimate the optimal heat balance among the existing buildings, and the following results are found:

1. In terms of individual energy system optimization, the office and apartment buildings have the potential to reduce their primary energy consumption compared with the results of the empirical design method. If a distributed energy system was established among the office and apartment buildings, primary energy consumption can be reduced significantly. The results showed the distributed energy system has the potential to reduce energy consumption.
2. The optimal system combination (applicable machinery capacity and machinery division) and optimal operation schedule of energy systems are selected effectively using the GA method. Thus, this method can be applied to optimal design for energy systems.

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