OPTIMAL DESIGN METHOD FOR BUILDINGS & URBAN ENERGY SYSTEMS USING GENETIC ALGORITHMS

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ABSTRACT

In this study, a new optimal design method for buildings and urban energy systems is proposed. Also its applicability is analyzed through a simple case study. Multi Island Genetic Algorithms (MIGA) are adopted for this optimization. This method has two optimization steps, selection of equipment capacity and selection of system operational planning. These optimization steps are calculated simultaneously. The results showed that the proposed method has the potential to be applied to very complex energy systems and achieve significant improvements.

KEYWORDS

Energy system, Optimal Design, Multi Island Genetic Algorithms

INTRODUCTION

Energy conservation in the building sector is now in great demand given the increased attention throughout the world in a view point of global environment. Because of advances in technology for building facilities, many choices are available when designing an energy system in a building or in an urban area, such as cogeneration systems, triple-effect absorption refrigerators, high-efficiency air source heat pumps, etc. Although so many choices exist, it is difficult to make a quantitative evaluation and to decide which energy system is the best, i.e. the lowest cost or the minimum environmental impact. Reasons for such problems include:

- Numerous combinations of equipment can be considered when designing systems.
- Operational efficiency of the system is highly dependent on how it is used.
- Prediction of energy demand when designing buildings is very difficult.

In order to resolve these problems, there are some researches on optimization methods for operational planning of energy systems using linear programs (G. Sundberg and D.Henning 2002). Under such methods, the relationship between energy-input and energy-output is assumed to be linear. However, with technological progress such as “inverter control” for machine operation, functions concerning energy input/output cannot be considered to be linear. Also, energy efficiency is highly dependent on equipment size and the operational load factor. Therefore, a new optimal method which can be applied to nonlinear problems is required for improved optimization.

Since the last decade, optimization methods for solving nonlinear optimization problems have advanced steadily. Write and Hanby (1987) applied the direct search method, but there may be some inaccuracy if boundary conditions are encountered. On the other hand, the Genetic Algorithms (GA) introduced by Holland (1975) have been applied to a diverse range of scientific, engineering, and economic problems. GAs are very suitable for handling complicated optimization problems with nonlinear, discrete and constrained search spaces. Huang et al. (1997) adopted GA for heating, ventilating and air-conditioning (HVAC) control problems. Also Obara et al. (2003) applied this method to the control problems of energy systems consisting of fuel cells, thermal storage, and heat pumps, etc. Write et al. (2002) applied GA to investigate multi-objective (building energy cost and occupant thermal discomfort) problems to identify the optimal pay-off characteristics. Hongwei et al. (2006) applied GA to mixed integer and nonlinear programming problems in an energy plant in Beijing, and made a detailed economic investigation by changing the economic and environmental legislative contexts.

In this paper, a new optimal design method for energy systems is proposed. This method optimizes both equipment capacity and operational planning simultaneously by using MIGA. It will be helpful for engineers who design energy systems of buildings or urban areas. Moreover, the application validity of the method was examined by means of a simple case study.

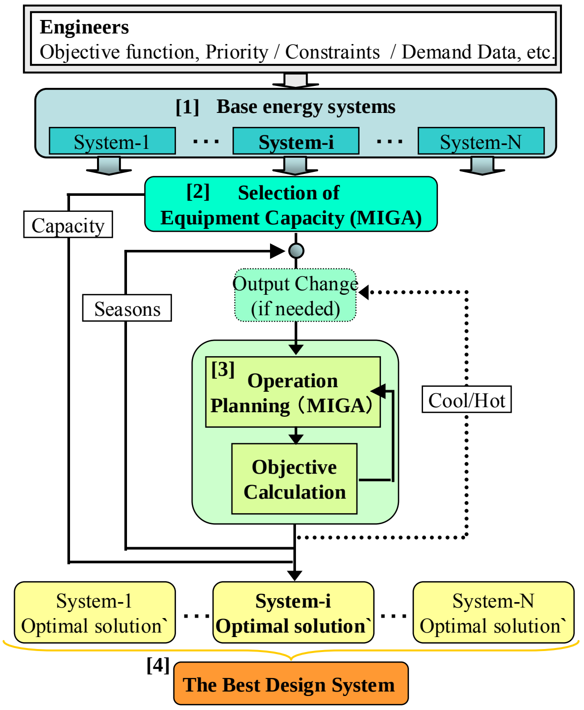

Figure 1 Optimal Design Process using MIGA

OUTLINE OF THE OPTIMAL DESIGN METHOD

Structure of Optimal Method

Figure 1 shows a flow of the optimal design method proposed here. There are four steps to achieve optimal planning.

1) Selection of the basic systems, which are characterized by the difference in type of equipment composing each system.

2) Optimization of equipment capacity. (Using MIGA)

3) Optimization of the operational planning of each energy system. (Using MIGA)

4) Selection of the best designed system by comparing each local optimal solution.

In the 1st step, "enumerate selection" among the basic energy systems is conducted, rather than "optimal selection". These basic energy systems are prepared as a database. The 2nd and 3rd steps are the optimization stages. These optimization problems, both equipment capacity and system operation, cannot be resolved separately due to the strong relationship between capacity and operation. Thus, these two steps are solved simultaneously. In the final 4th step, the best energy system which scores the highest rating among all local optimal solutions of each base system is selected as the optimal solution.

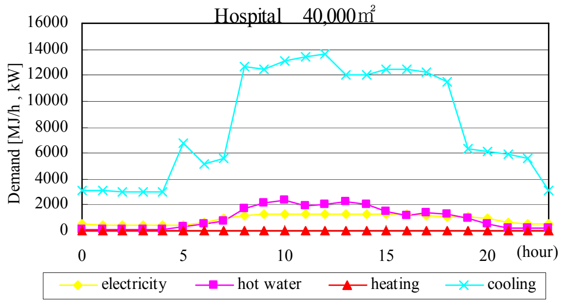

Figure 2 Demand Data

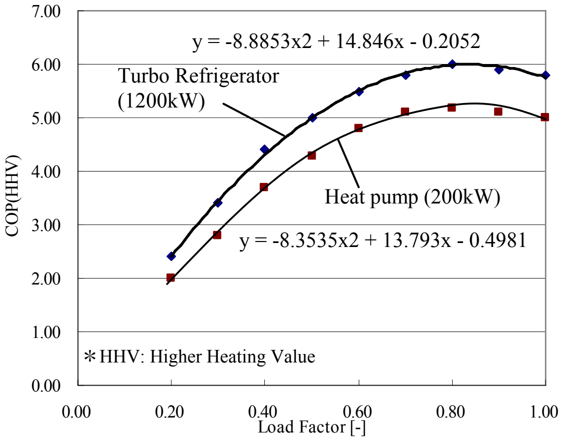

Figure 3 Equipment Data (for example)

Input Data

The main data used in these optimal calculations are as follows:

Energy Demand Data

Default data from the "Computer Aided Simulation for Cogeneration Assessment & Design III" (CASCADE III) released by The Society of Heating, Air-Conditioning and Sanitary Engineers of JAPAN is used. Figure 2 shows the data applied in this paper.

Equipment Data

Figure 3 shows an example of the equipment performance. With recent technological progress, such as "inverter controls" for equipment operation, functions concerning energy-input and energy-output have become nonlinear. A database of equipment performance is prepared and used in the calculation programs.

Application of Genetic Algorithms

GA is a method of solving optimization problems by imitating the evolutionary process based on the mechanics of Darwin's natural selection. Since its introduction by Holland (1975), GA has been applied to a diverse range of scientific, engineering and economic problems. In GA programs, the optimum solution candidate, which is termed an "individual", is considered to be a living entity. As per the evolution of organisms, each individual's

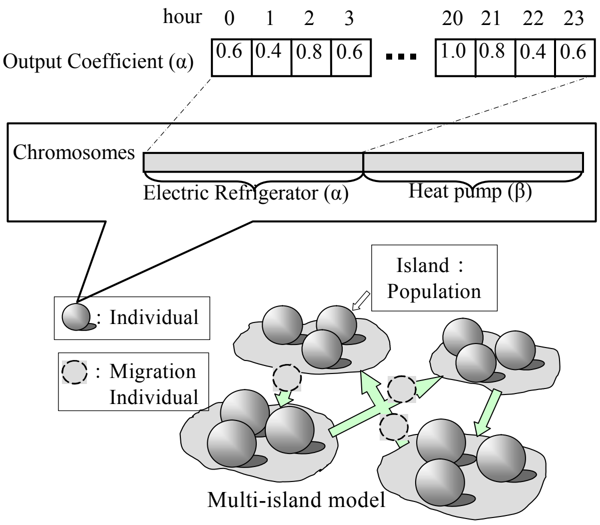

Figure 4 Diagrams of MIGA operations

information is described by sign rows called "chromosomes", which match the individual and the chromosome one to one. GA performs genetic operations such as selection, crossover, and mutations to the chromosomes of each individual, and the subsequent fitness (objective function) of each individual is calculated for evaluation. The individual with the highest fitness value of all the enquired individuals becomes the optimum individual. Moreover, a more efficient GA called a "Multi-island Genetic Algorithm (MIGA)" (R. Tanese 1984) is used in this research. MIGA involves a distributed genetic algorithm. The feature of this method is that the population in one generation is initially divided into several sub-populations called "Islands". And the genetic operations are performed independently on each Island. This independency enables the solution to avoid converging partial optimum. The exchange of individual information, termed "migration", is carried out periodically between Islands. Figure 4 shows ideal diagrams of the MIGA for the operational control optimization. Each cell in the "chromosomes" corresponds to a time division, and a rate of operational load would be arranged in each cell.

OPTIMIZATION ANALYSIS

To examine the validity of this optimal design method, analysis for a unit building was investigated experimentally.

Before this analysis, a simple-case analysis was conducted (K. Komamura and R. Ooka 2006). In this case, only the operational planning was optimized by using MIGA. Figure 5 shows a comparison between the optimal solution based on MIGA and the "correct" solution. "Correct" solution was derived by comprehensive calculation in which all of the operation plans were examined. Here, the optimal solution from the MIGA shows good agreement with the "correct" solution, even though it has a few discrepancies.

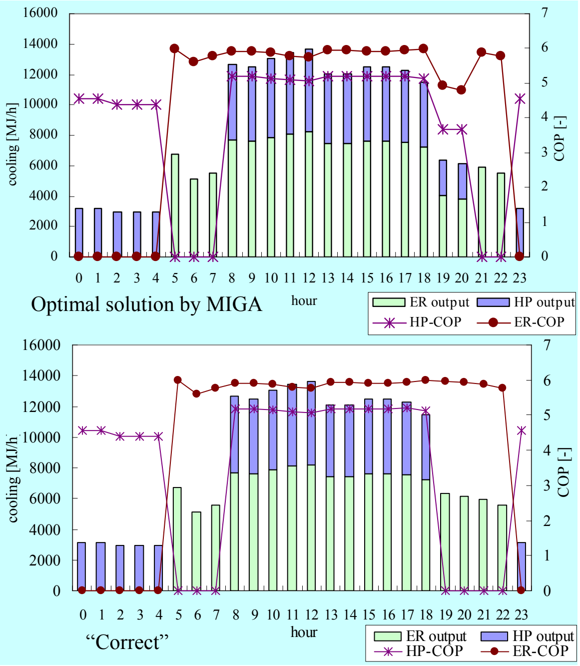

Figure 5 Optimal solution and "correct" solution

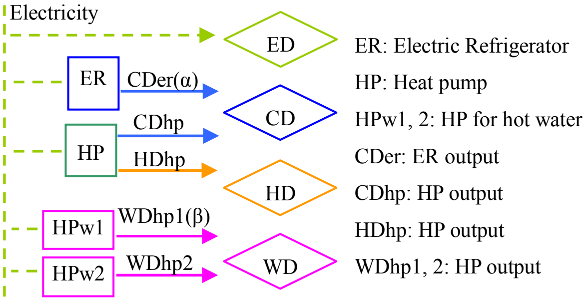

Figure 6 Energy system

Table 1 Variables in optimization

Capacity	
ER	1600, 1900, 2200, 2500, 2800 [kW]
HP1	700, 1000, 1300, 1600, 1900 [kW]
HPw1	450, 500, 550, 600, 650, 700 [kW]
HPw2	50, 100, 125, 150, 175, 200 [kW]
Load Factor	
Cooling (ER)	α_{i}(i=0_23): (0 , 0.2, 0.4 , 0.6 , 0.8 , 1.0)
Hot water (HPw1)	β_{i}(i=0_23): (0 , 0.2, 0.4 , 0.6 , 0.8 , 1.0)

In this paper, MIGA is used in two stages, capacity optimization and operational optimization. An analytical outline is described below.

Analysis Conditions

1) Objective Building: Hospital in Tokyo, Total floor area; 40,000 m^2
2) Analysis term: A representative day in Aug. (24h) In this term, energy demand for heating (HD in Fig.6) is 0 [MJ] through 24hours.

Table 2 MIGA parameters

MIGA parameters	Capacity selection	Operation planning
Size of Sub-Population	5	8
Number of Island	2	3
Population size	10（5×2）	24（8×3）
Number of Generation	30	250
Rate of Migration	0.5	0.5
Interval of Migration	5	5
Rate of crossover	1	1
Rate of mutation	0.01	0.01

3) Energy System: The objective energy system is shown in Fig. 6. In this study, only one system is analyzed. There are two heat pumps for hot water supply (HPw). Operational optimization problems are in Cooling Demand (CD) and Hot Water Demand (WD).

4) Variables: Shown in Table 1. Further details are as follows:

- Equipment Capacity: Set 5-6 types of capacity to each type of equipment composing the energy system.
- Operational Plans: Combination of the 24 coefficients (Load Factors) representing hourly-output of the electric refrigerator [CDer (α)] and HPw1 [WDhp1 (β)] are optimized by using MIGA. Other outputs (CDhp and WDhp2) are dependent variables for CDer and WDhp1.
- “Load Factors” are coefficients representing the rate of energy output against equipment capacity. However there are some modification of these coefficients for not to over-output beyond the demand.

5) Objective Functions: The amount of CO_2 exhaust and energy consumption converted to primary energy. Coefficients for calculating these functions are 690g-CO_2/kWh, 9,830kJ/kWh [electricity], and 1,960g-CO_2/Nm^3, 46,047kJ/Nm^3 [gas].

6) Constraints: The main constraints applied to this analysis are as follows:

- If Heating Demand (HD) is 0 MJ for 24h, heat pump for cooling/heating (“HP” in figure 6) is automatically changed to “cooling” operation mode.
- To avoid extreme hourly changes in equipment load, there is a penalty when the hourly load difference is over 60%.
- To avoid frequent ON/OFF operation, the minimum running time is set to 2 hours. Here is also a penalty when this rule is broken

Parameters

Table 2 shows the MIGA parameters in this study. To determine the accuracy of the optimization, parameters are decided by checking the effect of the parameters on the optimal solution. Figure 7 shows the effect of the generation number on the optimal solution. 250 is selected as the number of generations.

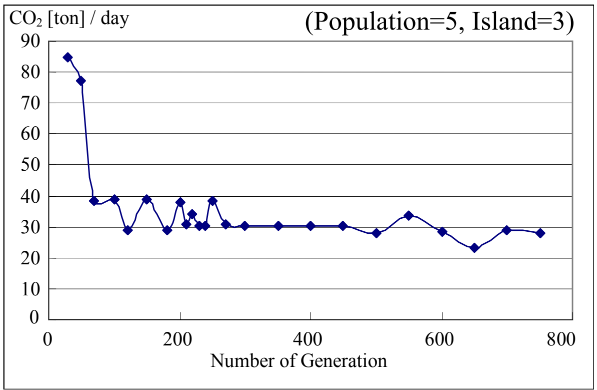

Figure 7 Effect of the number of generations on the optimal solution accuracy check

Table 3 Optimization results

Selected Capacity			
ER 2,500 (kW)	HP 1,600 (kW)	HPw1 600 (kW)	HPw2 100 (kW)

Selected Operation Plans

	hour	0	1	2	3	4	5	6	7	8	9	10	11
α		0	0	0	0	0	1.0	1.0	1.0	0.6	0.4	0.6	0.6
		12	13	14	15	16	17	18	19	20	21	22	23
	.....	0.6	0.4	0.4	0.4	0.4	0.4	0.4	1.0	1.0	1.0	1.0	0
	hour	0	1	2	3	4	5	6	7	8	9	10	11
β		0	0	0	0	0	0	1.0	1.0	1.0	0.2	0.2	1.0
		12	13	14	15	16	17	18	19	20	21	22	23
	.....	0.2	0.2	0.2	0.2	1.0	0.4	0.6	1.0	1.0	0	0	0

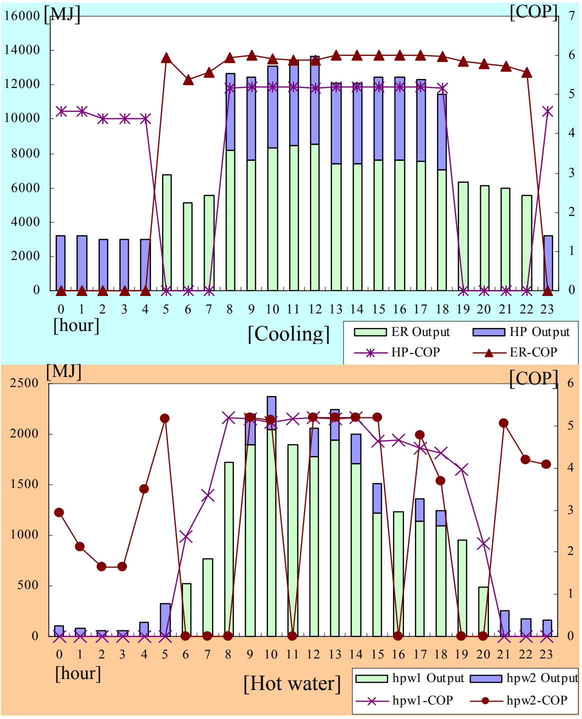

Figure 8 Results of “Operational Plan”

RESULTS & ANALYSIS

Results of this research are given in Table 3 and Fig. 8. The optimal solution for operation is illustrated in the chromosomes shape.

Cooling Operation

In the capacity optimization step, ER: 2,500 kW and HP1: 1,600 kW are selected as heat sources for cooling which can realize efficient operation. The total capacity is 4,100 kW (=14,760 [MJ/h]), which represents about 10% over the peak for the Cooling Demand (≈13,660 [MJ/h]). Here, smaller equipment such as ER: 2,300 kW or HP: 1,300 kW can be selected under the same constraints. However, if those smaller heat sources are selected, the operational load will be around 100% of its capacity. This results in lower efficiency compared with the optimal result, at which equipment can be operated at 70~90% of capacity. This is because the functions of the equipment efficiency are nonlinear, and this method can take into consideration nonlinear characteristics.

Also in the operational planning step, each equipment is loaded to about 80~90% of each unit's capacity for the peak hours, not that one equipment is loaded 100% of its capacity and another is loaded to meet the rest of the demand. Here, the characteristics of nonlinear functions are also taken into account. As a result, a higher COP can be realized.

These results show the advantage of the proposed optimal design method, which can optimize both equipment capacity and operation planning simultaneously. Additionally, for hours with a low Cooling Demand (23~4), only smaller equipment is selected. In this way, the COP can be kept at a high level.

Hot Water source Operation

In the capacity optimization step, HPw1: 600 kW and HPw2: 100 kW are selected for the hot water source equipment. This results in two equipment units, which have sufficient difference in capacity. This results from high "Head" of demand fluctuation. To be more specific, because Hot Water Demand is nearly "0" (lower than 100 [MJ/h]) during the night and peaks at 2,000 [MJ/h], two equipment units with enough difference in capacity are effective for coping with the hourly demand changes. However even these optimal capacities, COP is under 2 for a few hours. This is a limitation of adopting to demand with only two equipment units. Furthermore, as it becomes advantageous in numerical calculations, frequent ON/OFF operation is observed. Generally this is not good for equipment from a maintenance point of view. This will be a challenge to be solved in the future.

The total amount of CO_2 exhaust is 23.11 [t/day]. This figure represents about 135 [kg/year·m^2] bearing in mind energy demand distribution for each season. Compared with public data for the amount of CO_2 discharged from existing hospitals in Tokyo, which is about 140-190 [kg/year·m^2], this optimal solution shows good efficiency.

Conclusion

1) A new optimal design method for energy systems which can optimize both equipment capacity and its operation planning is proposed.
2) By conducting a simple analysis applying this method to a hospital, the validity of the method has been confirmed.
3) It becomes clear that there is possibility for equipment being operated at low efficiency inevitably, according to the characteristics of energy demand. Division of equipment capacity and/or effective constraints that are well suited to actual operations should be considered in the future.

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