Building Shape Optimization for Sustainable Building Design-part (1) investigation into the relationship among building shape, zoning plans, and building energy consumption

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ABSTRACT

To realize sustainable building design, improving energy efficiency by architectural passive design is essential at the conceptual design stage. At this stage, building shape such as building floor shape, arrangement, and orientation are important considerations in energy-saving building design because these variables have a significant impact on environmental performance (Flager, 2007[1)]). Many scholarly studies concerned with building shape optimization and energy consumption have been conducted. However, most of these studies only considered building shape as mass volume, with little mention of the relationship between building zoning and energy consumption in optimization. In the design of concrete buildings, zone planning elements such as core arrangement, which has significant impact on building planning design, must be considered. As a goal of this study, we aim to develop a design method to provide valid reference data on building shapes, suggesting solutions to minimize building energy consumption. We developed a building energy calculation model coupled with a shape optimization program using a genetic algorithm. Using this, we optimized building shape and a zone plan for minimizing energy consumption for lighting and AC. With the calculation results, we confirmed the impact of such parameters on building operation energy. Pareto optimal solutions are distributed with different tendencies by core zoning. By the difference in core zoning plans, optimal shape solutions change in respect to window ratio and aspect ratio.

KEYWORDS

Optimization, Genetic algorithm, Building energy simulation

INTRODUCTION

In order to realize sustainable building design, it is necessary to improve the energy efficiency of buildings. As the first step in developing of passive design methods, studies to improve energy efficiency by optimizing building shapes have been conducted. For example, Wang[2)] pointed out that making decisions regarding building shape was a very important element at the early stage of design and that it had strong impact on building energy consumption. However, the problem is that the consideration of energy efficiency at the primary design stage is usually based on the designer's personal experience or understanding. Reference solutions for energy saving are needed for comparison with other architectural conditions. So this study aims to develop a design method at the early design stage that provides reference data on the relationship among building shapes, zoning plans, and energy consumption. This paper claims application of a genetic algorithm works in green building design that considers not only external shape design but also interior zoning design.

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RESEARCH METHODS

We conducted optimization calculation of building shapes and plans for minimizing both the AC and the lighting energy consumption. Primary energy consumption by AC and by lighting are the object functions. The design parameters are the building floor shape, the building orientation, the window ratio of four surfaces and the arrangement of core zones. For calculation, we used NSGA-II (elitist non-dominated sorting genetic algorithm), which suits multi-objective optimization like this.[3)] Through a case study, this paper presents how this genetic algorithm works in green building design.

CASE STUDY

1.Examination object

We assumed a mid-scale city hall as the object, located in Tokyo. The construction specifications of the building is shown in *Table 1*. The room size of each floor is 1200 m^2. The whole of the four-story building is the analysis object. The aspect ratio is manipulated within the limits of 1:3 to 3:1, keeping the floor area as 1200 m^2.The ceiling height is 3 m and the story height is 3.8 m on all floors. The window ratio is manipulated within the limits of 0% to 100% of a ceiling height of 3 m. The orientation is manipulated within the limits of -45 degrees to +45 degrees. Twenty percent of the floor space is set to be a core zone as public space. The core zone arrangement is selected from among 11 patterns (*Figure 2*). It contains four one-side core types, two double-side core types, five central core types. In this study, we deal with seven parameters, namely the aspect ratio of the floor shape, window ratios for each of the four surfaces (four parameters), building orientation, and core zone type. The variable regions of these parameters are shown in *Table2*.

***Table 1**. Construction Specifications (Staring from indoors)*

Outer Wall	Hard fiberboard 12 mm, Rigid polyurethane foam 25 mm, Plain concrete 150 mm, Mortar 34 mm, Tiles 3 mm	U=0.834W/m^2K
Roof	Expanded perlite board 9 mm, Air space 700 mm, Rigid polyurethane foam 50 mm, Plain concrete 150 mm, Asphalt shingle 2 mm, Cinder concrete 100 mm	U=0.424W/ m^2K
Window	Low-E insulating glass With blinds	U=2.000W/ m^2K
Floor	Linoleum 3 mm, Plain concrete 150 mm, Air space 700 mm, Expanded perlite board 9 mm	U=4.527 W/ m^2K

***Table 2**. Parameters settings*

Parameter	Limit	Remarks
Aspect ratio	20~ 60m	The Floor area is 1200
Window ratio	0~100%	For four surfaces
Building orientation	±45	
Core arrangement	11 types	

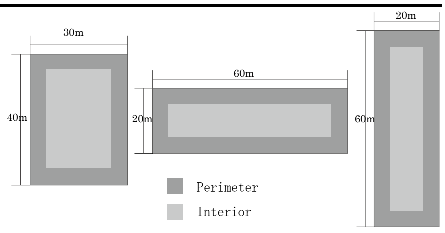

***Figure1**. Examples of floor shape*

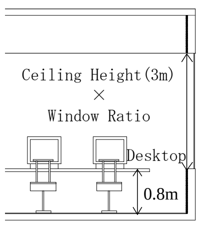

***Figure 2**. Window setting*

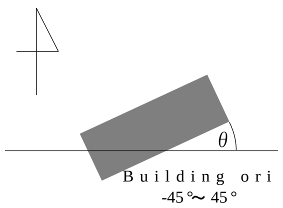

***Figure 3**. Building orientation*

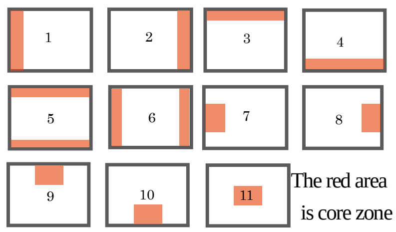

***Figure 4**. Core zone pattern*

2.Calculation settings of AC energy consumption

To calculate the energy consumption by AC, we used the building energy calculation program ESUM (Energy Specific Unit Management tool) developed by the Energy Conservation Center , Japan. We calculated the annual building energy consumption with standard weather data of Tokyo in 2005. With ESUM, we set zoning plans and operating and setting schedules. In this study, the area 5 m from the outer wall is set as the perimeter zone, 20% of the floor size is the core zone, and the left-hand part is the interior zone (*Figure 1* and *4*).

Saturday and Sunday are set as holidays. The real values of the lighting load and machine load of a general city hall are adopted. After calculating the heat load with ESUM, we calculate the possibility of reducing the proportion of lighting, which is removed from the AC load, and then calculate energy consumption. AC settings are shown in *Table 3* and *4*. Although general city halls are non-air-conditioned in spring and autumn, air-conditioning is assumed in this study during these seasons for considering usual office buildings. Default equipment in ESUM is used and the air change rate is set to 1.5 times / h and the primary energy coefficient is 9.76MJ/kWh.

Table 3*. Zoning settings* ※The human body load is 135W/person

Zones	Lighting load	Machine load	Human body load	AC system
Interior	13W/ m^2	7 W/ m^2	0.2 person/ m^2	Central
Perimeter	13W/ m^2	7 W/ m^2	0.1 person/ m^2	FCU
Core	non-air-conditioned			

Table 4*. AC settings*

Season	Month	Temperature	Humidity
Summer	6~9	26 ℃	50%
Spring, Autumn	4~5,10~12	24 ℃	40%
Winter	12~3	22 ℃	40%

3.Calculation settings for lighting energy consumption

We calculate the reduction in lighting energy consumption by daylight illumination according to the studies of Hirokawa et al.[4] in the following process. The calculated subject is only the office room.

(1) After setting the floor shape and the window ratios for each of the four faces, the geometric factor distribution is calculated. Measuring points are set at the heart of the lattice dividing the room at 1 m.

(2) With the luminous efficacy of daylight (η_c,η_d), direct and sky radiation from hourly weather radiance data are transformed into direct and sky illuminance (En, Es). η_c is used for the luminous efficacy of direct and sky radiation in clear weather and η_d is used for sky radiation in cloudy weather according to the studies[5] as reference (*Figure5*).

(3) The illuminance distribution of every working hour is calculated. Judging if direct radiation hits each wall in the solar and wall direction, we set exposed window shining with direct and sky illumination assumed to be uniform, and not exposed window shining with sky illumination. In this model, we ignore how direct sun beams enter the room. Blinds are considered as they reduce the entering daylight level as much as they reduce the heating load, not considering the entry angle.

(4) At each measuring point, if the illuminance is over 750 lx, we will turn off the light. And if it is less than 750 lx, we will turn on the light to compensate for the shortage. With the average reduction potential, we calculate the reduced lighting energy consumption and subtract the lighting load as well as the hourly room heat load, which is calculated by ESUM. Numerical formulas for calculating illuminance are shown in *Table 5* according to the studies[6]. The setting values are shown in *Table 6*.

Table 5. Formulas for calculating illuminance

Luminous efficacy (ηc, ηd)

$$\eta_c=59.3h^{0.1252} \quad [lm/W] \tag{1}$$

$$\eta_d=11.5C_F-5.93h^{0.1252}C_F+59.3h^{0.1252} [lm/W] \tag{2}$$

$$E_s=\eta c\times Qd\times \cos h\times \cos(A-A_v)+\eta\times Qs \ [lx] \tag{3}$$

(ηc or ηd is selected for η according to weather conditions)

Desktop illuminance (E)

$$E=(D_d+D_r)E_s=\{\tau MRU+(\tau MRU)\times 0.5(1+\rho_G)\times(S_w/S)\times(\rho_m/1-\rho_m)\}E_s \quad [lx] \tag{4}$$

h :Sun height[°], C_F :Cloud amount[-], Es :Diffuse sky illuminance[lx],Qd : Direct normal radiation[W/m^2], Qs : Sky radiation[W/m^2], A : Sun direction degree[°], A_v : Wall direction degree[°], D_d :Direct daylight factor[-], D_r :Indirect daylight factor[-], τ: Glass transmittance [-],M: Glass maintenance factor[-], R: Effective area ratio[-], U: Geometric factor[-], ρ_G: Ground surface reflectance [-], S_w : Window area[m^2], S:Room surface area[m^2], ρ_m : Indoor average reflectance[-]

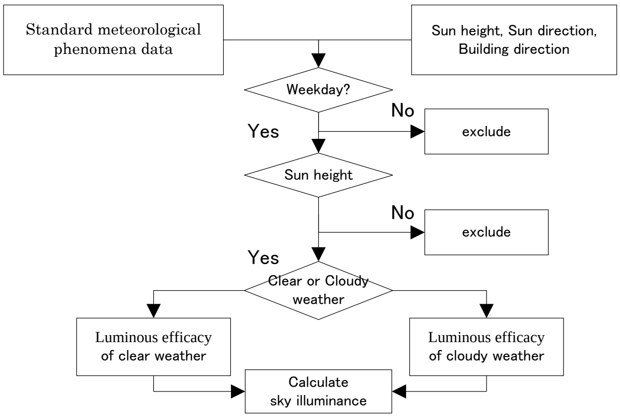

***Figure 5**. Diagram of daylight illuminance*

***Table 6**. Value for daylight illuminance*

τMR	ρm	Dr	ρG	ρ(ceiling)	ρ(wall)	ρ(floor)
0.7	0.4	0.025	0.2	0.7	0.5	0.2

4.Calculation settings of GA

We set 30 generations of 60 individuals and calculated the annual energy consumption 1800 times. The chromosome we used in this calculation consists of seven parameters, which are, in the following order, building orientation, window ratios (north, east, south ,west, in this order), east-to-west length and core type. The crossover rate is 0.5 and the mutation rate is 0.1.The settings are shown in *Figure 6*. The change of AC and lighting energy consumption through 30 generations is shown in *Figure 7*. For over 10 generations, each minimum value did not change so it can be said that calculation converges to some extent.

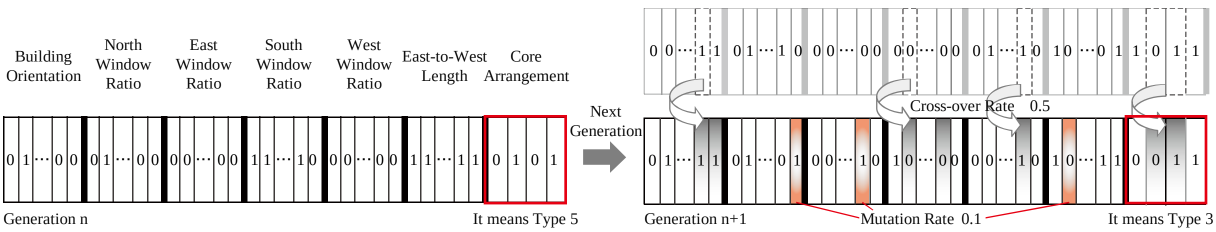

***Figure 6**. Settings of GA*

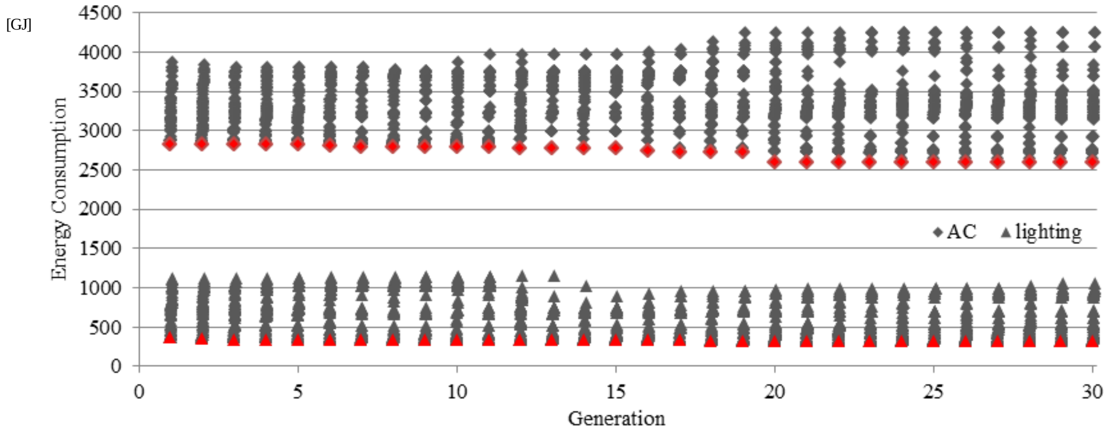

Figure 7*.* *Change of AC and lighting energy consumption through 30 generations*

RESULTS

The results of the last generations are shown in *Figure 8*. The form is similar to the form of Pareto optimal solutions, and it can be seen that changes of the core zone arrangement, the window ratio, and the aspect ratio result in a trade-off relationship between AC and lighting energy consumption. From this, it can be said that form optimization for two object functions is achieved. The values of the three solutions, namely A minimizing AC energy consumption, B minimizing the sum of AC and lighting energy consumption, and C minimizing lighting energy consumption, are shown in *Table 7*. A model with a nearly rectangular shape (35 m×34 m) with 20% ratio windows for each surface with center core zones is shown for the example model.

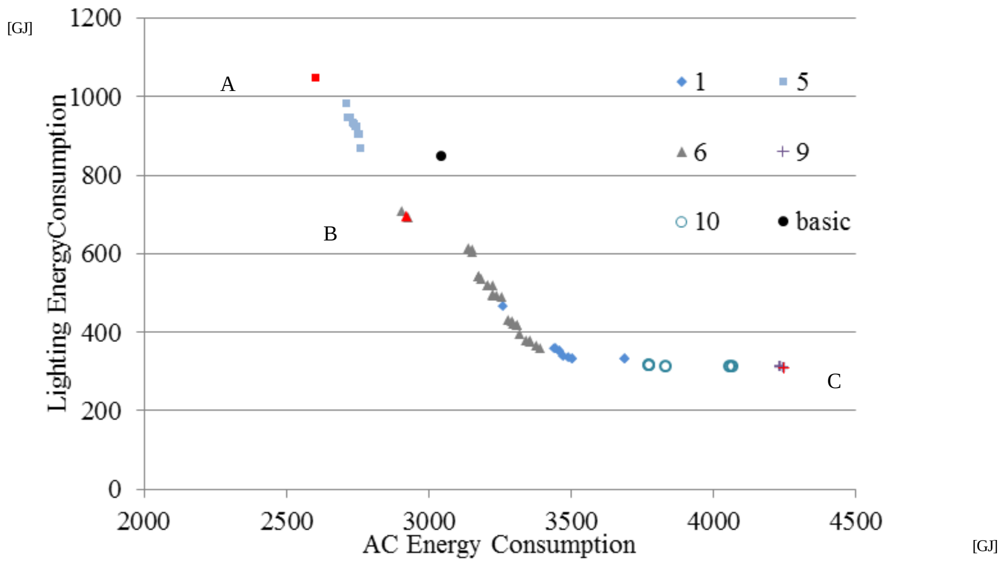

Figure 8*.* *Air-conditioning and lighting energy consumption in last generation*

Table 7*. Solutions which minimize energy of AC(A) ･Lighting(C) ･Sum of both(B)*

	Core	Direction (°)	Window area ratio (%) North	East	South	West	East-to-West Length(m)	South-to-North Length (m)	AC (GJ/year)	Lighting (GJ/year)
A	5	-8.7	0	40.8	0	10.7	48	25	2603.5	1048.9
B	6	-10.9	89.8	0	84.9	0	35	34	2906.4	705.6
C	9	41.8	98.2	97.1	99.8	47.6	60	20	4247.5	309.7
basic	11	0	20	20	20	20	35	34	3184.1	843.2

The exteriors of A,B, and C are shown in *Figure 9*. The blue zone is the window area. The dark gray zone is the core zone. Extended plans of A, B, and C are shown in *Figure 10*. The Central rectangle shows the floor plan and the rectangles on the four sides show each wall.

Solution A has core zones on the north and south sides and is long in the east-to-west direction with small windows on the east and west surfaces. Solution B has core zones on the east and west sides and is almost a square shape with large windows on the north and south surfaces. Solution C has a centralized core zone on the north side and is long in the east-to-west direction with large windows for each surface expect the west side.

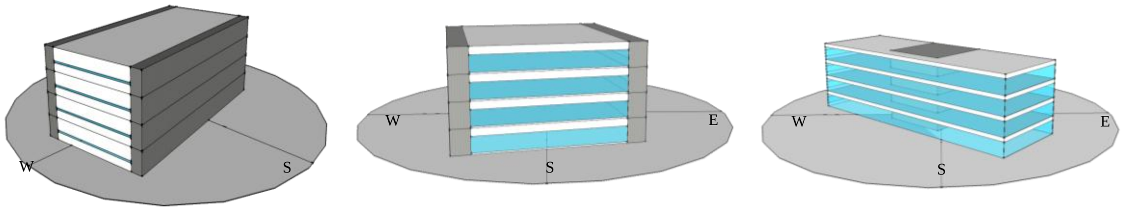

Figure 9. *Exterior (A) (B) (C)*

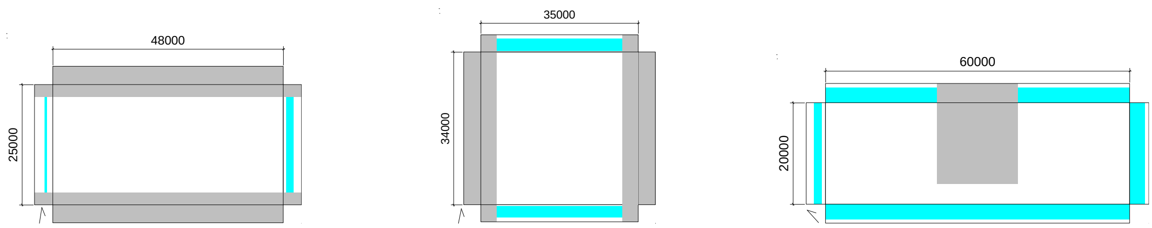

Figure 10*.* *Plans (A) (B) (C)*

DISCUSSION

In this session, we focus on the relationship between building plans and energy consumption. The relationship between average window ratio to AC and lighting energy consumption are shown in *Figure 11* and *12*. The relationship among east-to-west length, AC, and lighting energy consumption are shown in *Figure 13* and *14*. The result revealed that Pareto optimal solutions are distributed with different tendencies by core zoning.

Models in Type 1 with a west-side core, which cut solar radiation, have shapes that are long in the east-to-west direction with large windows to reduce lighting energy. This balances heat load reduction by core zoning and lighting load reduction with large windows. Models in Type 5 with north-and-south double-side core zones have shapes that are long in the east-to-west direction with windows that are not so large enough to reduce AC energy. It is mainly the south-side core zone that cuts sun beams and greatly reduces heat load. They are models that mainly aim reduce heating load. Their sum of AC and lighting energy is smaller than that of most of Type 6. Models in Type 6 with an east-and-west double-side core zones have large north and south windows to reduce lighting energy, but models whose sum of air-conditioning and lighting consumption is minimum are almost all square shapes. Due to the small surface area and east-and-west side core zones, these models reduce heat load and receive daylight from large windows. Models in Type 9 and 10 with a central core on the north or south side are long in the east-to-west direction and have about 80% windows on each side. The central core zone cannot block entering daylight and has large windows so it is able to receive daylight and greatly reduce lighting consumption. However, due to the large exposed windows area, the AC load becomes very large.

Focusing on the window surface ratio, it is in proportion to air-conditioning energy and in inverse proportion to lighting energy. But as mentioned above, in Type 5, 9, and 10, there is a moderate reduction in lighting energy and air-conditioning energy rises.

Focusing on the east-to-west length, as it becomes long and the depth narrows, the lighting load lowers because the center of the rooms can receive daylight. In contrast, the AC load rises because of enlargement of the surface area. In Type 5 and 6, there is a moderate enlargement of the surface area and narrowing of depth.

Shapes that are long in the north-to-south direction receive direct daylight from only either the large east or the west window and lighting energy cannot be reduced by much, but the heat necessary to acquire is too much and AC energy rises. So these models show a reduction in optimization because of the magnitude of total energy consumption. Thus, it can be seen that the shapes have a trade-off relationship between almost square shapes and long east-to-west shapes.

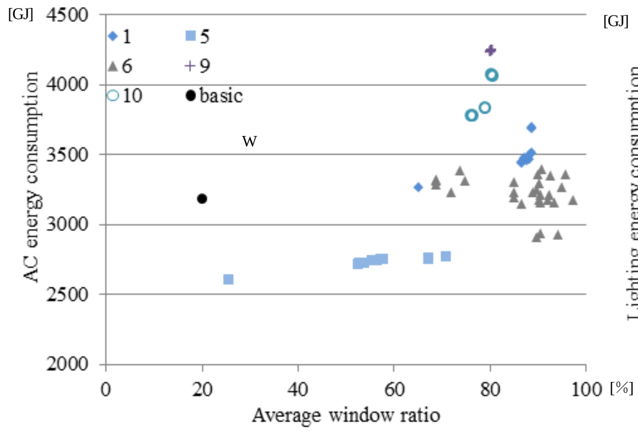

***Figure 10**. Relationship between average window ratio and AC energy*

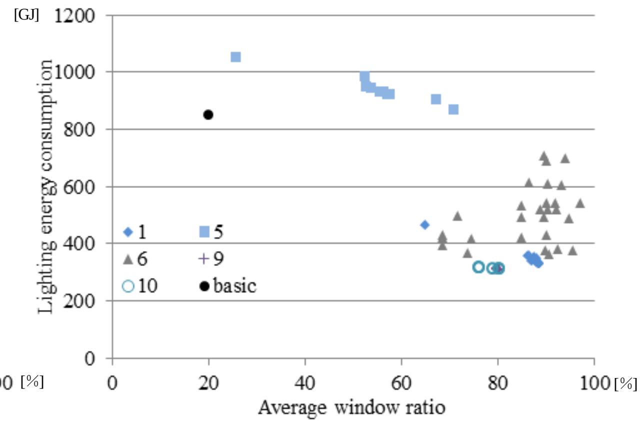

***Figure 11**. Relationship between average window ratio and lighting energy*

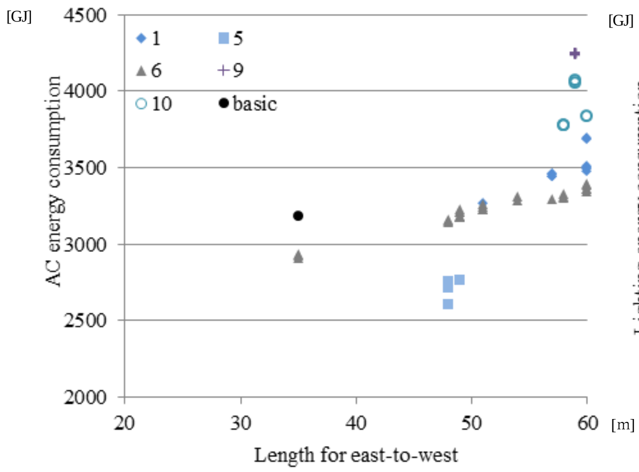

***Figure 12**. Relationship between length for east-to-west and AC energy*

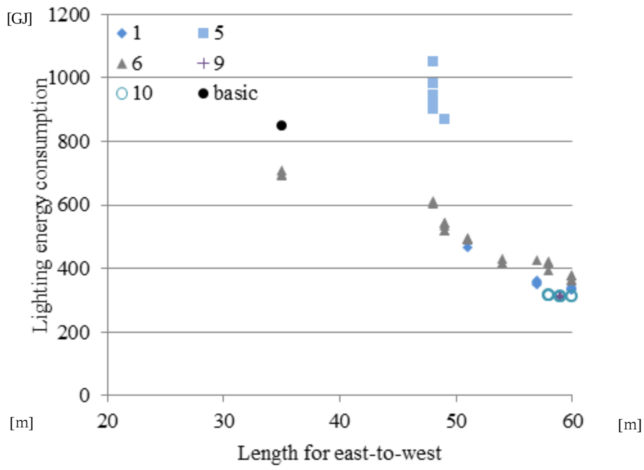

***Figure 13**. Relationship between length for east-to-west and lighting energy*

CONCLUSION

Multi-objective optimization is conducted with the objective functions(AC and lighting energy consumption) and the operating parts of the parameters, namely core arrangement, aspect ratio, building direction and window surface ratio for four surfaces. Pareto optimal solutions which minimize either object functions are observed in the last generation.

Different tendencies of optimized shapes by core arrangement are confirmed. There is a trade-off relationship because of the proportion of the surface area and the window ratio to air-conditioning, and inverse proportion to lighting energy is confirmed through quantitative value changes.

In the latest research to optimize building design using GA, a more complicated shape design has been considered, treating building shapes by defining nodes as geometric points (Yi, 2009[10)]).While building consideration in this study was limited to rectangular parallelepiped shaped, the floor plan was set to be the same area for four stories. A major purpose of this study is to focus on the impact of building internal zone planning design, not only external shape design. In the future, this study will be extended to consider further elements such as blind control, void plans, top light, equipment control, and so on.

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