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A Genetic Algorithm-Based Approach Design for Energy-Efficient Building in Thailand

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Abstract—**Building-related systems improvement bring the energy saving to cities. Shape, type of building, and building's time of use affect the electricity consumption. Only minimization of the energy consumption of the building causes exceeding in insulations or unreasonable option of lighting and air-conditioning systems which will increase initial cost of material and equipment to reach an unacceptable level for investment. Life-cycle cost evaluation is one of the best solutions to solve such problem. In order to choose suitable material and equipment, the application of genetic algorithm optimization was used in this study. Initial cost and energy cost were considered as objective functions to minimize the life-cycle cost of buildings. Office/school, hotel/hospital, and hypermarket/superstore building categories were evaluated as in Thailand's building energy code requirement. Different type of building results different energy consumption therefore the building systems are needed to improve in different way. The way of improving the life-cycle cost concerns, for example, period of time using during the day, shape and configuration, window-to-wall ratio, and required illuminance.**

Keywords-Building Energy Code; Building Design; Energy-Efficient Building; Genetic Algorithm; Life Cycle Cost

I. INTRODUCTION

Since 2000, Thailand's energy consumption grew at an average rate of 7% per annum. A quarter of the electricity consumption is due to the commercial sector [1]. Buildings in commercial sector have been recognized as one of the large and significant electricity consumer. This consumption is growing rapidly due to the expansion of building areas and use of energy-consuming equipment. Due to this growth, energy efficiency regulations for buildings need to be developed and implemented. Since 1998, Thailand has enforced the Building Energy Code (BEC), which regulates the standard of energy performance in buildings by setting minimum performance requirements for the three main systems: envelope system, lighting system, and air-conditioning system. Ten years after it enforcement, the BEC has been revised to make the standards more stringent and the economic principle of Life Cycle Cost (LCC) was used in setting the requirements. The new code regulates new building with a utilization area larger than 2,000 m^2. New buildings will not be permitted for construction, if its design performance does not comply with the code [2].

Buildings will endure for several decades and generations, a single best opportunity to assure the buildings are to meet a satisfactory level of energy efficiency occurs during the initial design phase as a lesson learned from experience that retrofitting buildings with energy efficient measure is not cost-effective. Building design is complex process in which many decisions are made about building related systems. Computer simulations have been proven to be powerful tool for studying and evaluating energy performance of building. Although simulation programs have been employed to create a clear understanding on all factors involved in interaction between design features, local climate, building use pattern, and mechanical and electrical systems in building, the iterative trial-and-error process of searching for a better solution is time-consuming and still rely on engineer intuition and experiences [3]. This presents a slow and tedious process and typically only a few scenarios are evaluated from within a large range of possible choices. Complexity of the process would increase with the increasing a number of design criteria to be met simultaneously.

This paper presents the features and performances of the building-related systems (i.e. envelope, lighting, and air-conditioning systems) that minimize the life cycle cost of building using a search and optimization technique of multi-objective genetic algorithm (MOGA). The analysis of the initial and energy operating costs are performed in Thailand's context.

II. GENETIC ALGORITHM

Genetic algorithm (GA) is known as adaptive heuristic search and optimization tools, which are categorized as global search heuristics based on the evolutionary ideas of natural selection and genetics. The basic concepts of GAs are designed to simulate processes necessary for evolution in natural systems [4].

Unlike classical search and optimization, a genetic algorithm is heuristic, which means it might not give the exact solution but it estimates a solution. Most real-life problems concern the estimation of solution rather than calculating it exactly. The estimation of solution is suitable for any complex system because it reduces time expend for solving the problem. It could be applied in wide range of studies in solving optimization problems, especially problems that are not well-structured and interact with large numbers of possible solutions such as most of the engineering problems [5].

III. METHOD OF STUDY

This sector describes first the details of the generic building model and the parameters configuring the building shape. Explanation next the formulation of the optimization problem: objective functions, problem variables, and problem constraints. Fig. 1 illustrates the method of study diagram which is comprised of three steps: data compilation, parametric study, and analysis of simulation results. The study was carried out for three building categories identical to those in Thailand's BEC.

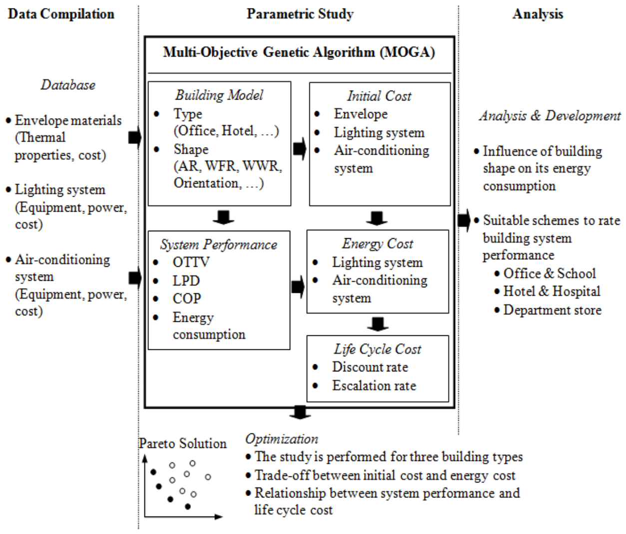


Figure 1. Method of study

A. *Generic Building Model*

A generic model of a rectangular building was formed and a set of parameters was assigned to configure the building model. The parameters comprise aspect ratio of the building plan (AR), window-to-wall ratio (WWR), wall-to-floor ratio (WTR), and building orientation.

In Fig. 2, parameter A and B denote respectively the length of longer and shorter sides of building façade. The floor-to-floor height of the buildings is set constant at 3.5 m.

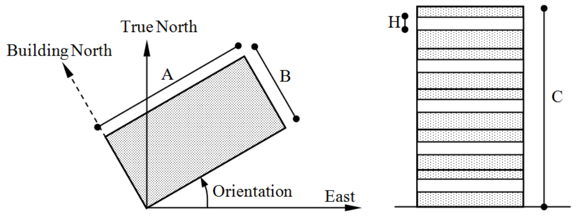


Figure 2 Configuration parameters of the generic building model

Four cases for each category of building were set with an aim to investigate the influence of building shape on the optimal design of the envelope system. For all cases, the building posses the same total floor area of 20,000 m^2.

Performance of each building system had been evaluated essentially for trading off between initial cost and operating energy cost of the building. Table III summarized the performance indices of the building systems including the data required for the evaluation.

TABLE I. FOUR CASES OF BUILDING SHAPE SET FOR THE STUDY ON OPTIMAL BUILDING DESIGN IN *OFFICE/SCHOOL* BUILDINGS AND *HOSPITAL/HOTEL* BUILDINGS

Total floor area (m^2)	20,000			
Storey (floor)	20			
Area per floor (m^2)	1,000			
Aspect ratio	1	2	3	4
Length of wall A (m)	31.62	22.36	18.26	15.81
Length of wall B (m)	31.62	44.72	54.77	63.25
Wall to floor ratio	0.44	0.47	0.51	0.55

TABLE II. FOUR BUILDING SHAPES SET FOR THE STUDY ON OPTIMAL BUILDING DESIGN IN *HYPERMARKET/SUPERSTORE* BUILDINGS

Total floor area (m^2)	20,000			
Storey (floor)	3			
Area per floor (m^2)	6,666.67			
Aspect ratio	1	2	3	4
Length of wall A (m)	81.65	115.47	141.42	163.30
Length of wall B (m)	81.65	57.74	47.14	40.83
Wall to floor ratio	0.17	0.18	0.20	0.21

TABLE III. PERFORMANCE INDICES OF THE BUILDING-RELATED SYSTEMS

System	Performance index	Required data
Envelope	OTTV and RTTV	Opaque wall material, glazing type, wall direction, area of opaque wall and glazing
Lighting	LPD	Type of lamp and ballast, power required by each equipment and illuminated area
Air-conditioning	COP	System cooling capacity and rated power consumption of chiller and other equipment in air-conditioning system

B. *Problem Formulation*

Source code was written in C language with MOGA concept for the search of Pareto solutions of the building systems that minimize the life-cycle cost of the building model. Equation (1.1), (1.2), and (1.3) express the formulation of the objective functions.

$$OF = Min\ (IC + EC) \tag{1.1}$$
$$IC = IC_{env} + IC_{ac} + IC_{lt} \tag{1.2}$$
$$EC = EC_{ac} + EC_{lt} \tag{1.3}$$

where

OF = Objective function,
IC_{env} = the annualized initial cost of envelope construction (Baht/(m$^2_{floor}$ · year)),
IC_{ac} = the annualized initial cost of air-conditioning system (Baht/(m$^2_{floor}$ · year)),
IC_{lt} = the annualized initial cost of lighting system (Baht/(m$^2_{floor}$ · year)),
EC_{ac} = the annualized energy cost of air-conditioning system (Baht/(m$^2_{floor}$ · year)),

EC_{lt}	=	the annualized energy cost of lighting system (Baht/($m^2_{\text{floor}} \cdot$ year)).

1) Initial Cost (IC):

The initial cost consist of costs of building envelope (excluding skeleton structure), lighting system (only lighting equipment), and air-conditioning system (only chiller). The initial costs of this study were derived and presented in term of annualized cost which accounts for difference of equipment life span in the systems and the value change of money with time.

Two main parts of wall are opaque wall and transparent wall. The opaque wall constructions cover the heavy-weight wall and the insulated wall. Six alternative types of transparent wall cover heat-reflective glass, colored float glass, single low-emissivity glass, and glazed window with shading device which leads to application of daylighting. Three alternative roof types cover noon-insulated and fiberglass insulated roof.

The initial cost of lighting system depends on the light luminaire type and the design illuminance level. For any working zone and circulation zone, the illuminance levels were set to 500 lx and 200 lx respectively. Six alternative lighting options cover standard fluorescent lamp, high-lux fluorescent lamp, T5 fluorescent lamp, standard magnetic ballast, low-loss magnetic ballast, and electronic ballast.

For air-conditioning system, the costs per unit cooling capacity (Baht/Ton of refrigeration) of chillers at different coefficient of performance (COP) were provided. Five performances of air-conditioning system with water-cooled water chiller were considered.

2) Energy Cost (IC):

Energy costs in this study were derived from the electricity used of lighting and air-conditioning systems. Building envelope influences the building electricity use in term of cooling load due to external heat gain. Equation (2) is called the energy equation which represents the total energy consumption of the building.

$$E_{pa} = \sum_{\substack{i=1 \\ i \neq j}}^{n} \left[\frac{A_{wi}(OTTV_i)}{COP_i} + \frac{A_{ri}(RTTV_i)}{COP_i} + A_i \left\{ \frac{C_l(LPD_i) + C_e(EQD_i) + 130C_o(OCCU_i) + 24C_v(VENT_i)}{COP_i} \right\} \right] n_h + \sum_{i=1}^{n} A_i(LPD_i + EQD_i)n_h \quad (2)$$

where

E_{pa}	=	total energy consumption of the building (W·h),
A_{wi}	=	an area of the wall that faces the exterior under consideration which includes areas of opaque wall and windows or transparent wall (m^2),
A_{ri}	=	an individual area of exterior roof for the considering zone (m^2),
A_i	=	an area of the considering zone i, for the case that a wall faces the exterior (m^2),
COP_i	=	the individual coefficient of performance of air-conditioning system for the considering zone,
LPD_i	=	the power density of lighting system for the considering zone (W/m^2),
EQD_i	=	the power density of equipment for the considering zone (W/m^2),
$OCCU_i$	=	the number of occupant per unit area in the considering zone (person/m^2),
$VENT_i$	=	the rate of ventilation air in the considering zone ($l/(s \cdot m^2)$),
n_h	=	number of operating hour (h),
C_l	=	the fraction of thermal power contributed to the load of the air-conditioning system by lighting,
C_e	=	the fraction of thermal power contributed to the load of the air-conditioning system by equipment,
C_o	=	the fraction of thermal power contributed to the load of the air-conditioning system by occupant, and
C_v	=	the fraction of thermal power contributed to the load of the air-conditioning system by ventilation.

Two types of constraints were considered in optimization model: continuous variable box constraint and discrete variable selection constraint. Box constraints give the boundary values of the continuous variables whereas selection constraints give predefined sets of alternatives for discrete variables.

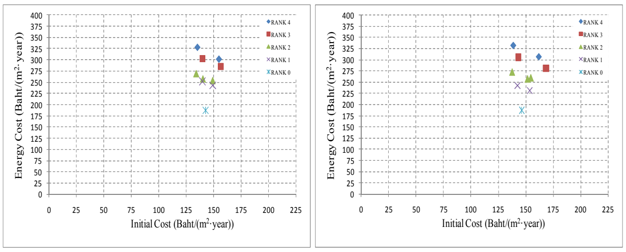
IV. RESULTS AND DISCUSSION

For all models in the simulation, the longer sides of the building facades were in a north-south orientation with total window-to-wall ratio of the building 0.35. For the envelope system, brick with no insulation was used for opaque wall, heat reflective blue-green Solartag was used for glazing window, and 0.15 m concrete was used for roof. Standard T8 fluorescent lamp with magnetic ballast was used as reference for lighting system and water-cooled water chiller with COP 5.02 was used in air-conditioning system.

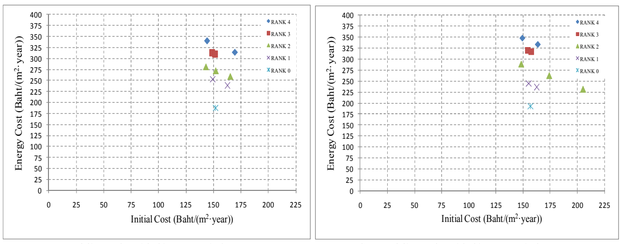
The reference building used in order to compare the simulation results are described as follow.

A. System Optimization of Office/School Building Category

The building LCC were ranked from 4 to 0 with Rank 4 being the highest LCC and Rank 0 being the lowest possible LCC. Although the members in each Rank have very close LCC values, the system configurations might be distinguished (different WWR value, different types of wall and glazing, lighting and A/C systems). However, it was observed from the simulations that the optimal system designs trend toward particular features such as insulation installation for opaque walls, shading the window with the concern of daylight utilization, using high efficient chillers and lighting equipments.

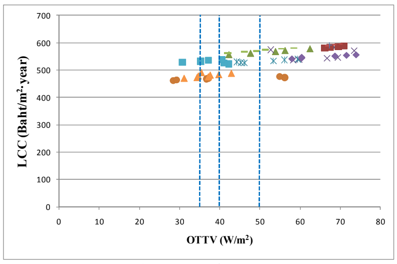


(a) Office building with AR 1 (b) Office building with AR 2

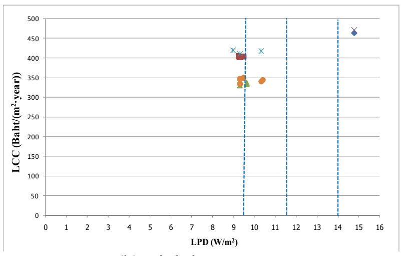


(c) Office building with AR 3 (d) Office building with AR 4

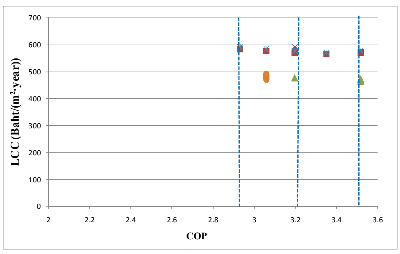
Figure 3 Plots of the Pareto front of the GA search (Office/School)



(a) Envelope system



(b) Lighting system



(c) Air-conditioning system

Figure 4. Correlation between system performance and LCC (Office/School)

Fig. 4 illustrates the plots of system performance and life-cycle cost for envelope system, lighting system, and air-conditioning system. In the plots, the performance of each building system was arranged into three levels. The lowest performance levels correspond with the performance requirements of Thailand's BEC while the highest performance levels correspond with that gives the minimum LCC of the building, as illustrated in Table IV.

TABLE IV. PERFORMANCE RATING SCHEME OF BUILDING SYSTEM FOR *OFFICE/SCHOOL BUILDING* CATEGORY

System	Performance/Efficiency		
	Fair	Good	Very Good
Envelope	40<OTTV≤50	35<OTTV≤40	OTTV≤35
Lighting	11.5 < LPD ≤ 14.0	9.5 < LPD ≤ 11.5	LPD ≤ 9.5
Air-conditioning	5.02<COP≤5.85	5.85<COP≤6.39	COP>6.39

Examination of the LCC of the office/school building category showed that improvement of the envelope system performance offers the greatest opportunity to minimize the building LCC. The envelope consists of brick with 25 mm Styrofoam and 12 mm gypsum board for the opaque wall, 6 mm ocean green float glass with shading device in order to use daylighting application for glazing window, using 0.15 m concrete with 75 mm fiberglass density 32 kg/m^2 is for roof of building aspect ratio 1 to 3 and 0.20 m concrete with 150 mm fiberglass density 32 kg/m^2 is for building aspect ratio 4. The improvement of the lighting system has the second highest influence on minimizing the LCC while improving the air-conditioning system has the lowest influence. The optimums LCC for the simulations are the use of T8 high lux fluorescent lamp with electronic ballast for the lighting system and water-cooled water chiller with COP 6.39 for the air-conditioning system.

B. System Optimization of Hypermarket/Superstore Building Category

Table V illustrates performance rating scheme of building system for hypermarket/superstore category which is leveled from simulation results. The lowest performance level, "Fair", correspond with the Thailand's BEC requirement. The level "Good" gives a lower LCC than the level "Fair" and the highest performance level, "Very Good", gives the minimum LCC.

TABLE V. PERFORMANCE RATING SCHEME OF BUILDING SYSTEM FOR *HYPERMARKET/SUPERSTORE* CATEGORY

System	Performance/Efficiency		
	Fair	Good	Very Good
Envelope	32.5<OTTV≤40.0	30.0<OTTV≤32.5	OTTV≤30.0
Lighting	15.0 < LPD ≤ 18.0	12.0 < LPD ≤ 15.0	LPD ≤ 12.0
Air-conditioning	5.02<COP≤5.85	5.85<COP≤6.39	COP>6.39

Examining the LCC of hypermarket/superstore building category, improvement of lighting system performance using T8 high lux fluorescent lamp with electronic ballast offer the greatest opportunity for minimizing the building LCC. Improvement of the envelope system by using brick with 25 mm Styrofoam and 12 mm gypsum board for opaque wall, 6 mm ocean green float glass with shading device for glazing window, 0.15 m concrete with 75 mm fiberglass density 32 kg/m^2 for roof of the hypermarket/ superstore building aspect ratio 1 to 3 and 0.20 m concrete with 150 mm fiberglass density 32 kg/m^2 for building aspect ratio 4 comes the second place for giving the LCC minimization. Improving the air-conditioning system using water-cooled water chiller with COP 6.39 shows the lowest influence on minimizing LCC for this building category.

C. *System Optimization of Hotel/Hospital Building Category*

Examining the LCC for hotel/hospital building category and the system performance, improving system performance of envelope system offers the greatest impact in reducing LCC. Brick with 25 mm Styrofoam as opaque wall, 6 mm ocean green float glass as glazing window, and 0.15 m concrete with 75 mm fiberglass density 32 kg/m^2 as roof give the optimum LCC for this building category, considering only envelope system. After the envelope system, the air-conditioning system offers the greatest impact on system performances with the use of a water-cooled water chiller with COP 6.39. The lighting system using T8 high lux fluorescent lamp with electronic ballast has the lowest impact on system performance.

Table VI indicates a performance rating scheme of building systems.

TABLE VI. PERFORMANCE RATING SCHEME OF BUILDING SYSTEM FOR *HOTEL/HOSPITAL* CATEGORY

System	**Performance/Efficiency**		
	Fair	**Good**	**Very Good**
Envelope	25.0<OTTV≤30.0	20.0<OTTV≤25.0	OTTV≤20.0
Lighting	8.5<LPD≤12.0	7.0<LPD≤8.5	LPD≤ 7.0
Air-conditioning	5.02<COP≤5.85	5.85<COP≤6.39	COP>6.39

V. CONCLUSIONS

This study presents features and performances of the building-related systems that minimize life-cycle costs of buildings using a search and optimization technique of multi-objective genetic algorithm. Different building categories have different ways of prioritizing the improvement of their systems in order to minimize the life-cycle costs. For office/school and hotel/hospital building categories, the most significant role to minimize life-cycle costs belongs to the improvement of envelope system. These two building categories have a high wall-to-floor ratio which allows enough thermal transfer from outside to have significant effect on temperature to rise up. On the other hands, this high ratio can be very useful for energy saving form lighting system by daylighting application. Lighting system and air-conditioning system come the second and the third places for these two building categories. For hypermarket/superstore building category where lighting shares significantly on electricity consumption, improvement of lighting system gives the lowest life-cycle cost compared to the other two systems. The envelope system improvement come the second priority and the air-conditioning system come the third priority for this building category. Improving three main building systems altogether always give the lowest LCC compared to one building system improvement. Notice that the described results are only for Thailand's context where using of the air-conditioning system is for cooling condition for all year.

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