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# Cost-Effective Model for Energy Saving in Super-Tall Building

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***Abstract:*** ***In many urban cities, super-tall buildings have been being constructed around New York and Chicago as the center since 1930 to improve the efficiency of land use and respond to new residential type. In terms of energy consumption, super-tall buildings are classified as a top energy consumption building. Also, as time passed, the degradation of energy performance occurs in super-tall buildings like general things so that these cannot show the initial performance planned in the design phase. Accordingly, building owners need to make a plan to apply energy saving measures to existing building during the operation phase. In order to select energy saving measures, calculus-based methods and enumerative schemes have been typically used. However, these methods are time-consuming and previous studies which used these methods have problems with not considering the initial construction cost. Consequently, this study proposes a model for selecting an optimal combination of energy saving measures which derives maximum energy saving within allowable cost using genetic algorithms. As a contribution of this research, it would be expected that a model is utilized as one of the decision-making tools during the planning stage for energy saving.***

***Keywords: Super-tall Building, Cost-effective, Energy Saving, Genetic Algorithm***

## I. INTRODUCTION

### *A. Background and Objective*

In many urban cities, the densely populated phenomenon is shown due to rapid industrialization and urbanization. In order to improve the efficiency of land use and respond to new residential type, super-tall buildings have been constructed around New York and Chicago as the center since 1930 [5]. It could be possible since steel skeletal structures are developed as a method to construct super-tall buildings [9].

On the other hand, in terms of energy consumption, super-tall buildings typically use several times energy comparing to low-rise buildings under the same area [7]. In super-tall buildings, heating and cooling loads incurred by building envelope are higher than low-rise buildings so that HAVC and other electrical equipment require high energy consumption in order to keep up a comfortable living space [2]. In addition, since the degradation of buildings is progressed as time passed, these cannot show the initially planned energy performance [10] and could be used as a factor affecting the increase of energy consumption in super-tall buildings along with architectural characteristic. Furthermore, because life cycle of super-tall building is over 200 years, it is required to repair and replace the deteriorated equipment during operation. In particular, the second to fourth generation super-tall buildings constructed after the industrial revolution is now showing the deterioration so that its owners need to make a plan to reduce energy consumption and save energy cost.

According to the previous research related to selecting energy saving measures (ESMs), optimal methods such as calculus-based methods and enumerative schemes have been typically used to select ESMs. However, these methods have problem taking a lot of time to search for optimal energy saving measures. Also, since the previous research did not consider the initial cost as a criterion along with the amount of energy saving, it is difficult to draw cost-effective ESMs. Accordingly, it is necessary to select an optimal combination which derives maximum energy saving within allowable cost when making an energy saving plan during operation of super-tall buildings.

The purpose of this study is to develop a model to select an optimal combination consisting of energy saving measures using genetic algorithms. Also, this research considers the initial cost for each ESM along with the amount of energy saving. As a contribution of this research, it will be possible to derive the maximum energy saving within the allowable cost so building owners utilize this model as a decision-making tool on the planning stage for energy saving.

### *B. Scope and Methodology*

This research focuses on the planning stage for energy saving in existing super-tall buildings and is conducted in the following procedures and methodology.

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(1) The problem with optimization methods which the previous research utilized is analyzed, and then drives an adequate methodology based on the analysis results.

(2) After considering the basic principle and search method of genetic algorithms, application of genetic algorithms to this research is suggested.

(3) The classification scheme of energy saving measures is established and a way to calculate the amount of energy saving and the initial cost for each ESM is drawn.

(4) The possible considerations during search process are investigated and the cost-effective model is developed using genetic algorithms.

## II. Preliminary Study

### A. Optimization Methods

According to 'Optimization theory', the goal of optimization is to find optima and improve search methods [1]. In this context, methods mean the process for finding optima using optimization algorithms and they are defined as optimization methods. These can be divided into calculus-based methods, enumerative schemes and random search algorithms [3].

Calculus-based methods are used to find optima in local area so it is easy to converge on a local extreme. Enumerative schemes are considered to find an optimum satisfying the objective function in the search space of various shapes and sizes. However, since the actual search area is too large and discontinuous, it has trouble decreasing the search efficiency and taking a lot of time to find a global optimum. Random search algorithms are most widely used as an optimization method by researchers and find an optimal solution by randomly exploring all the search area.

### B. Research on Selecting Energy Saving Measures

The research on selecting ESMs during operation has been steadily conducted in domestic and abroad.

Park [10] suggested a method to select optimal ESMs for an improvement of building envelope insulation using enumerative schemes. Also, it was possible to represent cost-effective alternatives using initial costs as well as the amount of energy saving as criteria. Kari A. [6] used the environmental ($CO_2$) and functional (initial costs, energy saving) performance index as criteria when selecting energy saving measures. Also, enumerative schemes were utilized as a research methodology. Hong et al. [4] created various energy saving scenarios adequate to elementary schools and then compared the amount of energy saving and life cycle cost (LCC) for each scenario. However, the aforementioned methods like enumerative schemes needs a lot of time to find the global optimum (i.e. there are many ESMs). Thus, it is inappropriate to apply enumerative schemes to this research.

On the other hands, Suh and Park [12] presented a selection method using genetic algorithms as one of random search algorithms in order to make up for the shortcomings of enumerative schemes. Also, it demonstrates excellence in the optimization performance of genetic algorithms by comparing the results between genetic algorithms and heuristic approach. However, it cannot derive cost-effective ESMs because initial costs are not considered as a criterion.

### C. Genetic Algorithms

Genetic algorithms (GAs), introduced by John Holland in 1975, are one of the random search algorithms and find an optimal solution in the extensive search area [3]. The concept of GAs is based on the survival of the fittest and natural selection which are claimed by Darwin [11]. According to Darwin's theory of evolution, creatures that live in certain environment repeat the mutation and crossover as generations are progressed. In this process, the most suitable creatures in a given environment are survived.

The search process using genetic algorithms is described as follow (refer to Figure I). Firstly, various chromosomes are produced under constraints set in the early stage. Secondly, when various chromosomes produced during a specific generation cannot satisfy the stop condition, the initial number of chromosomes is reproduced. In this step, the chromosomes having better performance are selected as a superior entity through suitability evaluation, which are replicated to next generation. Thirdly, the chromosomes selected as a

TABLE I
PREVIOUS RESEARCH ON SELECTING ENERGY SAVING MEASURES

| Previous Research | Main Content | Optimization Method | Limitation |
|---|---|---|---|
| Park (2004) | · Suggesting a method to select optimal ESMs for an improvement of building envelope insulation.<br>· It was possible to represent cost-effective alternatives using initial costs as criteria with the amount of energy saving. | Enumerative Scheme | · This method takes a lot of time to find a global optimum where there are many ESMs. |
| Kari Alanne (2004) | · Using the environmental ($CO_2$) and functional (initial costs, energy saving) performance index as criteria. | | |
| Hong et al. (2012) | · Creation of various energy saving scenario adequate to elementary schools.<br>· Comparing energy saving and LCC for each scenario. | | |
| Suh and Park (2011) | Presenting a selection method using genetic algorithms in order to make up for the shortcomings of enumerative schemes.<br>It demonstrates excellence in the optimization performance of genetic algorithms by comparing the results between genetic algorithms and heuristic approach. | Genetic Algorithms And Heuristic Approach | · It cannot derive cost-effective ESMs because initial costs are not considered as a criterion. |

superior entity are recombined by exchanging the genetic information with each other according to the crossover probability. Fourthly, some of genes introduce new genes according to the mutation probability. The chromosomes generated by this process repeat the above steps until satisfying the stop condition. Also, in this step, the parameters significantly affect the improvement in quality of the optimal solution and efficiency of problem-solving process.

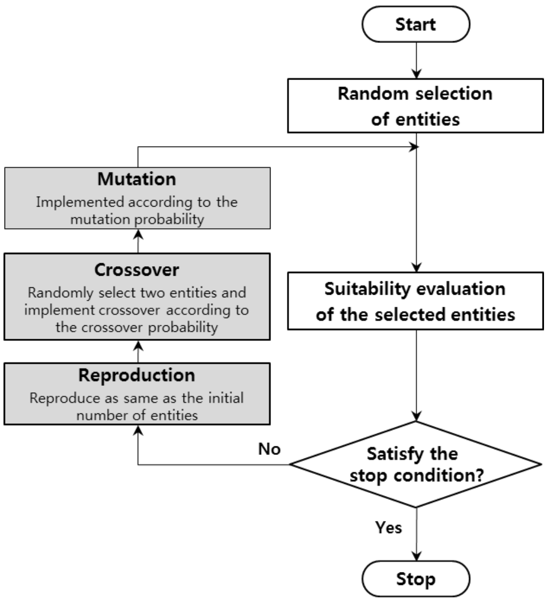


FIGURE I
PROCESS OF GENETIC ALGORITHMS

## III. ESTABLISHMENT OF ENERGY SAVING MEASURES

### A. Classification of Energy Saving Measures

In order to reduce energy consumption in existing buildings, energy performance should be improved by repairing and replacing the deteriorated equipment with the high-efficiency and low-energy consuming. In this research, these actions are defined as energy saving measures (ESMs) and hierarchically classified according to saving sector, solution, and option (refer to Figure II).

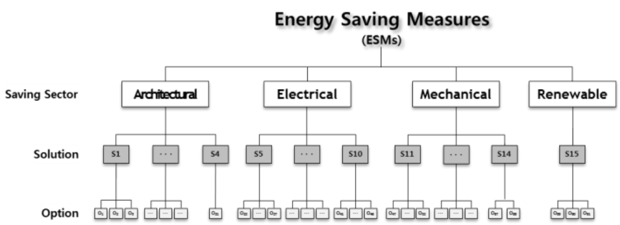


FIGURE II
HIERARCHICAL CLASSIFICATION OF ESMS

### B. Unit Cost for Energy Saving Measures

The initial cost is the important criterion when searching for an optimal combination. Michael and John [8] proposed tender price indices and building cost indices to estimate the initial cost for each ESM in a retrofit project. Tender price indices reflect the cost that is incurred by bidders in bidding phase, which include profits. Meanwhile, building cost indices refer to the cost incurred by constructors in construction phase and exclude profits. According to this previous research, tender price indices are more accurate to estimate the initial cost than building cost indices so it is utilized as a unit price. Also, the initial cost consists of material, labor, and expense.

## IV. INITIAL COST AND ENERGY SAVING FOR ENERGY SAVING MEASURES

### A. Application of Genetic Algorithms

Genetic algorithms randomly determine whether ESMs are used in the search process and produce a chromosome as shown in Figure III, that is to say a combination. Each number which is listed with genes (A to J) means that 0 is unused and 1 is used for nth ESM. Also, each gene includes the information about the initial cost and the amount of energy saving, which are utilized when determining an optimal combination. The chromosome shown in Figure III presents a combination consisting of 10 ESMs and A, C, D, H, I, and J are used for energy saving.

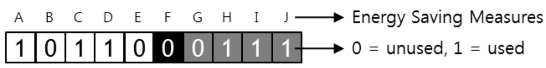


FIGURE III
EXPRESSION OF COMBINATION

### B. Initial Cost Estimation

The initial cost for each ESM is estimated by multiplying the unit price in ESM DB with quantity. Formula (1) shows a way to calculate the initial cost for each ESM.

$$C_n = C_{n \cdot u} \times Q_{n \cdot q} \quad (1)$$

Where, $C_n$ : initial cost for $n^{th}$ ESM
$C_{n,u}$ : unit price for $n^{th}$ ESM
$Q_{n,q}$ : quantity for $n^{th}$ ESM

Therefore, the total cost is estimated by considering whether ESMs are used as shown in Formula (2).

$$C_t = \sum \alpha_n \cdot C_n \quad (2)$$

Where, $C_t$ : total initial cost
$\alpha_n$ : $0 = \text{unused}, 1 = \text{used for } n^{th}$ ESM

### C. Energy Saving Calculation

Energy consumption in existing buildings is reduced by applying ESMs and the amount of energy saving is used as a criterion along with the initial cost. In order to calculate the amount of energy saving, this research uses two equations as shown in Formula (3) and (4).

$$S_n = E_e - E_n \quad (3)$$
$$S_n = E_e \times e_r \quad (4)$$

Where, $S_n$ : energy saving for $n^{th}$ ESM
$E_e$ : existing energy consumption
$E_n$ : new energy consumption
$e_r$ : percentage of energy saving for $n^{th}$ ESM

Formula (3) is a calculation method based on the characteristic of ESMs. The amount of energy saving is calculated by subtracting the new energy consumption from the existing. For instance, in the case that a 20W incandescent lamp is replaced with 7.2W LED bulb, the amount of energy saving is calculated like Formula (5).

$$\begin{aligned} S_L = &\ (20W \times 1EA \times 250d \times 8h \times 0.001) \\ &-(7.2W \times 1EA \times 250d \times 8h \times 0.001) \\ = &\ 25.6kW \end{aligned} \quad (5)$$

Formula (4) is an equation by multiplying the percentage of energy saving (%) derived from an experiment with the existing energy consumption. It could be used in case of not knowing variables such as hours, quantity, and characteristic of equipment. For instance, when installing the counter sensor in toilet, the amount of energy saving is calculated by Formula (6).

$$S_c = 20kWh \times 80\% = 16kW \quad (6)$$

Therefore, the total energy saving for ESMs selected by genetic algorithms is calculated by Formula (7).

$$S_t = \sum(\alpha_n \times S_n) \quad (7)$$

Where, $S_t$ : total energy saving
$\alpha_n$ : 0 = unused, 1 = used for $n^{th}$ ESM

## V. Development of Cost-Effective Model for Energy Saving

### A. Consideration in Selection Process

#### 1) Compatibility

As described in section 3.1, there are a lot of solutions and options in each of saving sectors and the options included in the same solution are classified according to equipment data. Thus, there would be unavailable ESMs to be applied to existing buildings at the same time. Kari A. [6] defines whether ESMs can be selected at the same time as compatibility, which is possible to occur in solution and option layer.

In case of solution layer, for instance, it is unnecessary to install inside and outside insulation together and this compatibility can be expressed as shown in Formula (8).

$$\alpha_{\text{inside insulation}} + \alpha_{\text{outside insulation}} \leq 1 \quad (8)$$

Where, $\alpha_{\text{inside insulation}}$ : 0 = unused, 1 = used
$\alpha_{\text{outside insulations}}$ : 0 = unused, 1 = used

Also, in case of option layer, LED bulb is one of the solutions in lighting sector and includes many options according to watts. If 7.2W LED bulb is selected as an ESM, any LED bulbs should not be selected. In this example, compatibility could be expressed as shown in Formula (9).

$$\sum \alpha_n \leq 1 \quad (9)$$

Where, $\alpha_n$ : 0 = unused, 1 = used for $n^{th}$ ESM

#### 2) Correlation

The purpose of energy consumption in buildings can be divided into cooling, heating, lighting, and device. This research calculates the amount of energy saving according to the relationship between ESMs and energy consumption, which is defined as correlation. In addition, the amount of energy saving is divided into the 1st and 2nd energy saving according to this correlation. The 1st energy saving is the basic energy saving occurring in the purpose of energy consumption directly related to ESMs. For example, insulating materials improve the performance of building envelop insulation and then reduces energy consumption in cooling and heating. Meanwhile, the 2nd energy saving is additional saving incurred by the 1st energy saving. For example, the 1st energy saving of LED bulb leads to reduction in cooling loads. Consequently, energy consumption in cooling is reduced. Figure IV shows the correlation between ESMs and energy consumption with an example.

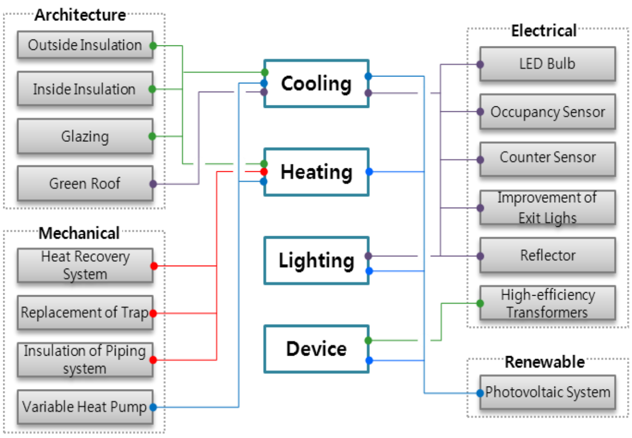


FIGURE IV
CORRELATION BETWEEN ESMS AND PURPOSE OF ENERGY CONSUMPTION

### B. Configuration of Cost-Effective Model

This research developed a cost-effective model for energy saving in existing super-tall building, which is divided into three modules like Figure V.

*1) Input module by user*

Users input the information about existing buildings according to saving sectors; architecture, electrical, mechanical, and renewable energy (refer to Table II). This input value is transmitted to characteristic DB in module 3 and utilized when calculating the amount of energy saving and the initial cost. Also, users separately input the annual energy consumption for each purpose, which is utilized when calculating the amount of energy saving according to formula (4) in section 4.3.

TABLE II
EXISTING BUILDING INFORMATION (EXAMPLE)

| | Area of Exterior Wall | Area or Interior Wall | Area of Slave | Area of Window Glass |
|---|---|---|---|---|
| Unit | $m^2$ | $m^2$ | $m^2$ | $m^2$ |
| Quantity | 1,428 | 1,384 | 631.5 | 407.7 |

*2) Decision module by user*

Users investigate whether ESMs in each saving sector were applied or not to the existing building and then draw the available ESMs to make a combination. In addition, users input the characteristics of each ESM, which is utilized when calculating the amount of energy saving.

*3) Selection module by operator*

In this module, optimal ESMs are selected using the information collected from module 1 and 2, ESM database, and the operator of genetic algorithms. The search process using genetic algorithms is described as below.

Firstly, after a user set up the objective, constraints, and parameters for that case, the operator of genetic algorithms produces various combinations consisting of 0 and 1. In this step, ESMs which were not installed in existing buildings have ‘0’ or ‘1’, whereas ESMs already installed in existing buildings always have ‘0’.

Secondly, the operator discerns the compatibility of ESMs which are included in each combination. If the combinations are comprised of compatible ESMs, they are transferred to next step.

Thirdly, the operator calculates the initial cost and the amount of energy saving targeting only the survived combinations. The initial cost is estimated based on the information about the existing building collected in module 1 and the unit cost established in ESM database. In case of the amount of energy saving, the information to use is different according to the calculation methods. A method by Formula (3) in section 4.3 utilizes the information about the existing building collected in module 1 and the characteristics of each ESM inputted in module 2. On the other hands, Formula (4) is based on the information about the percentage of energy saving and the annual energy consumption for each purpose.

Finally, the operator selects an optimal combination which satisfies the objective function under constraints. In this step, each generation produces new combinations by mutation and crossover and these repeat the above steps until satisfying the objective function.

## VI. CONTRIBUTION

In many urban cities, super-tall buildings have been being constructed in order to improve the efficiency of land use and respond to new residential type. In terms of energy consumption, super-tall buildings are generally classified as a top energy consumption building. In particular, since the life cycle of super-tall buildings are more than 200 years, it is required to pay attention to the deterioration of the buildings. Therefore, building owners need to make an energy saving plan such as repair and replace of deteriorated equipment and materials during operation of super-tall buildings.

This study analyzed the previous research related to the selection of energy saving measures and then found the problem with not considering the initial cost as a criterion and the low efficiency of search method. In order to make up for these shortcomings, this research developed a cost-effective model for energy saving using genetic algorithms as one of random search algorithms. Consequently, this research is significant that a cost-effective model makes it possible to select an optimal combination consisting of ESMs when making an energy saving plan in existing super-tall buildings. The developed model has the applicability as follows; firstly, it can be possible to select ESMs which derive the maximum energy saving within allowable cost. Thus,

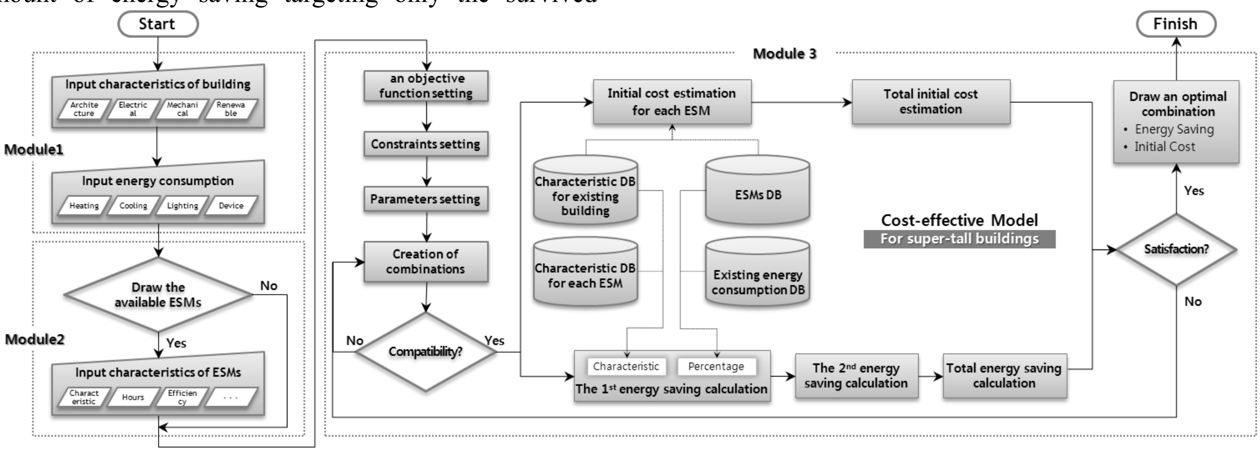


FIGURE V
PROCESS OF COST-EFFECTIVE MODEL

since the operating cost is reduced, building owners can use this cost incurred by energy saving to improve other building services. Secondly, it can be possible to estimate the minimum cost required to achieve the energy saving goal. However, the results of this research are merely development of a model so the future study is required as follow. Firstly, it is necessary to establish ESM DB available during operation of super-tall buildings and unit price DB. Secondly, a cost-effective model needs to verify its logic by implementing a case study. Thirdly, since the amount of energy consumption and the initial cost are considered as criteria, it is expected that the future study needs to consider operation and maintenance cost and usability for each ESM.

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