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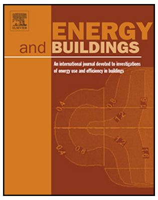

A systematic approach for energy efficient building design factors optimization

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ABSTRACT

We developed a systematic methodology to minimize the building heating and cooling loads using experimental design and non-sorting genetic algorithm to select optimal sets of building design factors. The analysis of experimental design provided a ranked list of important through less important factors design factors affecting the building heating and cooling loads. The factors related to window performance were found to be most significant ones. The non-sorting genetic algorithm offered piecewise linear pareto front lines where the optimum building design factor sets for minimum heating and cooling loads lie. The results of experimental design analysis were statistically verified against TRNSYS simulation results. It was found that the ratio of the efficiencies of heating and cooling systems affected the optimum passive building design, hence the active and passive parts of a building should be considered simultaneously in a coupled manner for the optimum design of net zero energy buildings.

1. Introduction

The building sector accounts for about 22% of total domestic energy consumption in Korea in 2010, and it is expected that this share would grow continuously with the improvement of life standard and income increase. Korean government announced a plan that every new residential and non-residential building should meet the requirement of net-zero energy consumption for the approval of construction starting from the year 2025, i.e., the new buildings should be net zero energy buildings (NZEBs). Architects and construction engineers started to find ways to confront with the reinforced energy standards, and they realized that they should take the following steps to meet the goal [1]. As the first step, the building heating and cooling loads should be minimized through the optimal selection of the passive building design factors. Second, high-efficiency active building heating and cooling systems should be selected to pair the new building design of low loads to yield low energy consumption. Finally, select the techno-economically affordable renewable energy sources to match the lowered energy demand of the optimized building.

There are many research articles on the optimization of the building envelope design and the methodology for it. Caldas et al. [2] reported the development and application of a Genetic Algorithm (GA) based optimization tool for the placing and sizing of the windows in an office building. Malkawi et al. [3] developed a decision support evolution model using GA as the evolution algorithm and computational fluid dynamics (CFD) as the evaluation mechanism. Wright et al. [4] applied multi-objective GA to identify the optimum design considering the building energy cost and occupants discomfort. Wetter and Wright [5] compared the performance of optimization algorithms, and explained the coarse convergence criteria as the source of the discontinuities of the cost function for the building design and control problems. Wang et al. [6] used life cycle cost and life cycle environment impact as two cost functions in the optimization of building envelope design with building orientation, aspect ratio, window type, window-to-wall ratio, wall type, wall layer, roof type and the layers of roof as factors using GA. Jaffal et al. [7] applied Design of Experiments (DOE) to obtain simple polynomial functions of building design factors to predict building heating demand. Magnier and Haghighat [8] performed optimization study on building design and operation considering thermal comfort and energy consumption.

In this study, a systematic statistical method was presented to determine the set of building design factors to minimize the building heating and cooling loads and energy consumptions using the fractional factorial design method, which used a subset of all possible combinations of design factors to ease the burden of exhaustive number of test runs using full factorial design while securing the prediction accuracy (refer to Montgomery et al. [9]), to consider all second order interactions. The dynamic simulations

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of building heating and cooling loads were performed, and the relations between the loads and the design factors were obtained statistically in a polynomial equation form, with which the pareto front of the optimum building design factor sets was determined. The relation between the optimum building envelope design sets and the selection of active building heating and cooling systems were discussed.

2. Theory

2.1. Baseline building model selection

We reviewed the design drawings of 178 buildings in Korea together with researchers and architects in commercial companies, and it was analyzed that the buildings were about 20 to 40 stories and 70,000 m^2 of total floor area on average, and 1400 m^2 of average floor area. For the recently built office buildings, the total floor area tends to range between 40,000 and 100,000 m^2. The building core usually spans about 25–30% of total floor area, and its location can affect the window-to-wall ratio to vary building heating and cooling loads.

In this study, the impacts of the alteration of building design factors on building heating and cooling loads were analyzed for a representative floor of a reference building of exterior core. Analyzing the energy consumptions of each floor in the existing buildings, about 85% of total energy consumption occurred in the floors of reference type. Although the loads varied with the use of each floor such as lobby, restaurant, and office, the reference floor was selected as the office floor since most part of the office building was used for the purpose, and the reference building was assumed as a collection of multiples of office floor. There were usually mechanical rooms in the top floor, so that no special investigation was performed for the top most floor. Due to the limitation of the design factor number allowed and the difficulty to set the levels of design factors for DOE, the common design factors considered in the previous studies such as floor area (FA), building orientation (OR), ceiling height (CH), aspect ratio (AR), plenum height (PH), window-to-wall ratio (WWR), wall insulation (WI), window insulation (WDI), solar heat gain coefficient (SHGC) and air leakage (ACR) were selected for the current study. Although the shading could affect seriously the loads, it was not considered in the current study due to the difficulty of handling it as an example. Table 1 represents the specifications of the reference building together with the considered building design factors and levels of alteration in Table 2. The reference levels of building design factors were selected to comply with the latest Korean national standard and government guideline. In case of window-to-wall ratio, there was a guideline for the design of energy efficient building from Korean government [12] not to exceed 60%. Considering the area of the exposing core wall, the upper level of the value was assigned as 52%. The schedules for people, heating/cooling, and lighting were set according to ASHRAE 90.1-2004 standard. For the equipment schedule, which was not provided in ASHRAE 90.1-2004 standard, the hourly operation schedule for large office in the commercial reference building models of national building stock [11] was used. Seoul data in TMY2 weather file format were used as the reference weather. The floor was decomposed into four neighboring thermal zones (Office 1, Office 2, Office 3, and Office 4) plus an air-conditioned core zone as shown in Fig. 1, and a plenum space over them.

2.2. Experimental design

Solving an engineering problem means to find accurate functional relations between outputs and factors of a product or a process, and use them to design and improve the products or to refine and optimize the processes. The outputs represent the dependent variables, heating and cooling loads of a building in this study, where factors mean independent design variables like FA, OR, CH, AR, PH, WWR, WI, WDI, SHGC, and ACR, and levels of a factor are the different values of the factor considered.

Table 1
Summary of reference building.

Categories	Sub-categories	Value	References
Location	Seoul (Climate Zone 4) KR-Seoul-471080.tm2		[10]
Use		Office	
Size	Floor area (m^2)	1444	
	Air conditioned area (m^2)	1019	
	Floor height (m)	3.9	[11]
	Ceiling height (m)	2.7	[11]
	Window-to-wall ratio (%)	40	[12]
Wall *U*-value	External wall (W/m^2 K)	0.365	[13]
Window	*U*-value (W/m^2 K)	2.84	[13]
	SHGC	0.4	[13]
Tightness	Infiltration (ACH)	0.3	[14]
Internal heat gain	People (people/m^2)	0.1	[15]
	Lighting (W/m^2)	12	[13]
	Equipment (W/m^2)	16	[15]
Set temperature	Heating (°C)	26	[16]
	Cooling (°C)	20	[16]
Schedule	People		[17]
	Heating/cooling		[17]
	Lighting		[17]
	Equipment		[11]

Table 2
List of factors and their levels.

Factor	Symbol	Level	
		Low (−1)	High (+1)
Floor area (m^2)	FA	1000	2000
Aspect ratio (–)	AR	1	2
Orientation	OR	South	West
Window-to-wall ratio (%)	WWR	25	52 [12]
Ceiling height (m)	CH	2.4	2.9
Plenum height (m)	PH	0.8	1.2
Wall insulation (W/m^2 K)	WI	0.150	0.365 [13]
Window insulation (W/m^2 K)	WDI	0.75	2.84
SHGC (–)	SHGC	0.2	0.7
Air leakage (ACH)	ACR	0.1	0.3 [14]

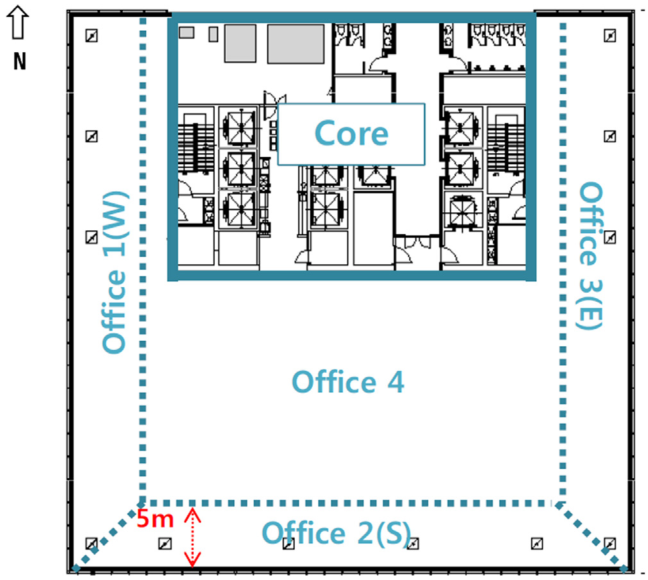

Fig. 1. Floor area schematics of the reference building.