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Simulation-based optimization of an integrated daylighting and HVAC system using the design of experiments method

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HIGHLIGHTS

- The IDHVAC system is optimized using the integrated meta-model and GA.
- The design of experiments method is applied to train the integrated meta-model.
- The GA-optimized models are compared with the reference model.
- The GA-optimized IDHVAC model shows the best performance among them.

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ABSTRACT

The use of daylight in buildings to save energy while providing satisfactory environmental comfort has increased. Integration of the daylighting and thermal energy systems is necessary for environmental comfort and energy efficiency. In this study, an integrated meta-model for a daylighting, heating, ventilating, and air conditioning (IDHVAC) system was developed to predict building energy performance by artificial lighting regression models and artificial neural network (ANN) models, with a database that was generated using the EnergyPlus model. The design of experiments (DOE) method was applied to generate the database that was used to train robust ANN models without overfitting problems. The IDHVAC system was optimized using the integrated meta-model and genetic algorithm (GA), to minimize total energy consumption while satisfying both thermal and visual comfort for occupants. During three months in the winter, the GA-optimized IDHVAC model showed, on average, 13.7% energy savings against the conventional model.

1. Introduction

Nowadays there is strong demand for environmental comfort in the workspace for health and productivity. In providing that, heating, ventilating, and air-conditioning (HVAC) and lighting systems use approximately 50–60% of a building's energy consumption to maintain thermal and visual comfort for occupants [1]. In addition, the use of solar heat and daylight in buildings, to save energy, has increased [2]. However, when daylighting and HVAC systems are separately controlled, energy efficiency and environmental comfort are often in conflict with each other [3]. Therefore, it is necessary to adopt an integrated control process for the two systems while satisfying environmental comfort. Since optimized control to achieve energy conservation and environmental comfort in buildings is a multi-dimensional and complex nonlinear problem, an effective and integrated optimization algorithm for these technologies also needs to be developed under various operating and geometrical conditions.

Optimization algorithms can be divided into two main categories: conventional gradient-based methods and gradient-free direct methods. Since building systems are very often nonlinear, the gradient-based optimization methods are inapplicable to most building studies. In contrast, the gradient-free methods are more suitable to building studies [4] due to the use of stochastic approaches. Stochastic population-based algorithms, such as the genetic algorithm (GA), particle swarm optimization, the hybrid algorithm, and the evolutionary algorithm, are the most frequently used methods in building performance optimization. The most well-known and widely accepted method is GA [5]. The GA shows excellent optimization performance in multi-input, multi-output non-linear systems [6]. The GA has been used to optimize setpoints of several devices in HVAC systems at a given time [7,8].

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Nomenclature

AHU	air handling unit
ANN	artificial neural network
CAV	constant air volume
CSTR	constraint
C_v (RMSE)	coefficient of variation of the root mean squared error
DOE	design of experiments
FCU	fan coil unit
GA	genetic algorithm
HVAC	heating, ventilating, and air conditioning
I	illuminance (lux)
IDHVAC	integrated daylighting and HVAC
MBE	mean bias error
OA	outdoor air
P	energy consumption (kW)
R^2	coefficient of determination
RF	relative flow rate based on the maximum value
Sch	on/off schedule (0 or 1)
T	temperature (°C)
t	time
U	overall heat transfer coefficient (W m^{-2} K^{-1})

Greek symbols

α	azimuth angle (°)
ϕ	slat angle (°)
γ	ratio (0–1)

Subscripts

AHU	air handling unit
art	artificial
day	daylight
DOE	design of experiments
E	equipment
FCU	fan coil unit
in	indoor
L	lighting
OA	outdoor air
out	outdoor
ref	reference
SP	setpoint
tot	total
t-1	previous time step
w	water

In building applications, simulations can be useful in several aspects for improving the design and integration of building control systems [9]. However, it is difficult to apply building simulation models to a population-based optimized control algorithm, such as GA, in real time because most models do not allow access to state variables [10]. One very efficient solution is to use a meta-model to imitate the behavior of the building model, and then to optimize individual control variables [4]. The artificial neural network (ANN) has been adopted for the meta-model because it has tremendous advantages in deriving and extracting accurate patterns from complicated data in the modeling of building systems [7,11–13]. Although the ANN can improve the accuracy of the model for an integrated system by using more hidden nodes, the network may then forecast out-of-samples very poorly [14]. This is the so-called overfitting problem. An early stopping method containing three data sets of training, testing, and validation parts [15] has been popularly used to avoid overfitting in a building system. However, despite using the early stopping method, it is still difficult to achieve both good prediction ability and a robust ANN model at the same time in a complex integrated system with limited training data. Therefore, in this study, the database was constructed using building performance simulations with the design of experiments (DOE) method to develop a robust meta-model in the global optimization process.

Even though various control and optimization methods in building systems have been developed, an integrated building control considering the simultaneous interactions of systems is still lacking. This impedes smart-grid initiatives and market penetration [16]. An optimization of the setpoints in an integrated daylighting and HVAC (IDHVAC) system presents a great challenge, because the IDHVAC system is a nonlinear, multivariable system. The objective of this study is to optimize the IDHVAC system for energy effective operation while considering environmental comfort. An integrated meta-model was developed to predict building performance using artificial lighting regression models and ANN models, with a database generated by the EnergyPlus model [17]. The setpoints of the IDHVAC system were optimized using the integrated meta-model and GA to minimize the total energy consumption in the heating season.

2. Experiments on the IDHVAC system

Fig. 1 shows a schematic of the IDHVAC system in a building. The IDHVAC system consisted of an HVAC system and a daylighting system. The IDHVAC system was installed and monitored in an office (6.35 m × 3.75 m) in a building in Seoul, Korea [18]. Table 1 shows the descriptions of the reference building and office. The HVAC system in the building consisted of direct gas-fired absorption chillers/heaters, a constant air volume (CAV) duct system, and a fan coil unit (FCU). A CAV box was connected to the AHU, to maintain thermal comfort by controlling the air flow rate to each thermal zone. The supply air temperature was controlled by modulating the water flow rates in the heating and cooling coils, respectively. The FCU was installed beneath the exterior window, to manage the thermal load through the window. In the experiments, we measured the temperatures and flow rates of the supply and return air, and the water in the FCU.

The daylighting system consisted of a motorized venetian blind (Somfy® LS40 motor), and a non-dimmable and two dimmable 96 W fluorescent lights. Generally, a venetian blind can be controlled by the slat angle and height. However, in this study, the motorized venetian blind was controlled by the slat angle at the full height, in order to investigate the thermal and visual performance of the IDHVAC system. The blind slat angle was controlled to accept as much radiation as possible, while preventing direct daylight from entering the room [18]. As shown in Fig. 1, the illuminance in the room was measured at two points by photometers with an accuracy of ±5%. The room temperature was measured by a thermocouple with an accuracy of ±0.2 °C. The power consumption of the fluorescent lights was measured using a power analyzer with an accuracy of ±0.1%.

3. Development of the system optimization model

As shown in Fig. 2, an integrated meta-model was developed to optimize the control variables, using a GA in real time. The integrated meta-model consisted of ANN models and artificial lighting regression models. The ANN models for the room temperature,