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Integrated and multi-hour optimization of office building energy consumption and expenditure

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ABSTRACT

An integrated approach was used to optimize energy use and expenditure of a RC-network model for five zones (four perimeters and one center zone) office building to control dimmable light, shade position, inside air temperature, and outside air flow rate. Parameters considered in this model were: (1) heat transfer, solar heat gain, and illuminance from window; (2) heat transfer from internal and external walls; (3) external walls heat storage; (4) internal heat gain from occupants and equipment; (5) ventilation rate; (6) cooling and heating systems load; and (7) illuminance and heat gain from artificial lights. Total energy consumption of artificial light, ventilation fan, heating and cooling systems was considered as objective function for optimization. The multi-hour optimization included minimizing total energy use and expenditure for single- or several-hour periods. Our analysis showed significant energy saving potentials by using building integrated multi-hour optimization. Comparing total energy use of the building assuming fixed control schedules with the integrated control of the systems showed yearly savings nearly 35% in electricity use for the simulated office building.

1. Introduction

Optimal operation of a building's systems is critical for reducing energy and maintenance costs, ensuring occupant comfort and maintaining indoor air quality. Optimizing a building's energy consumption requires an approach that allows devices and systems to interact with each other and controlled together to meet occupant requirements. Parameters that influence quality of indoor environment such as temperature, CO_2 concentration and indoor lights can be adjusted through integrated operation of controllers. Fig. 1 shows the relationship of zone controllers and indoor comfort parameters. Many buildings have multiple systems that typically work independent of each other. These systems include heating, cooling, lighting, ventilation, automated blinds, and domestic hot water. The control strategies of existing building systems are mostly based on local controllers or pre-defined relation between parameters. These control methods usually lead to non-optimal energy management and comfort [1]. Several case studies have documented significant energy savings potential by application of integrated control systems [2–4].

Previous works have mostly focused on application of integrated control on one zone or limited systems rather than the whole building and systems. Mathews et al. [5,6] and Vakiloroaya et al. [7] focused on HVAC system integration. Daylighting and illuminance control integration was investigated by Caicedo and Pandharipande [8], Shen and Hong [9], Mukherjee and Birru [10], and Rubinstein et al. [11]. Roche and Milne [12] investigated the effect of combining smart shading and ventilation.

Moreover, a variety of optimization methods have been applied in building control problems such as, linear and non-linear programming (LP and NLP) [13,14], genetic algorithm optimization technique [15–17], and dynamic programming (DP) [18]. Multi-hour integrated control algorithms for building energy management and their energy and cost savings potential are not completely investigated yet.

Gyalistras et al. [19] investigated the energy savings potential of simultaneous control of blinds, lighting, heating, cooling and ventilation in a single building zone. They compared whole-year hourly time step simulations with rule based control and model predictive controls for several factors (such as comfort range, air quality controlled ventilation, and facade orientation). The largest energy savings potential was found for the use of CO_2-controlled ventilation (average savings of 13–28%).

Sun et al. [20] developed a methodology to get a near-optimal control commands for the blinds, natural ventilation, lights and HVAC system jointly. Numerical simulation results showed that both traditional and integrated strategies can effectively reduce the total energy cost and the integrated control can save

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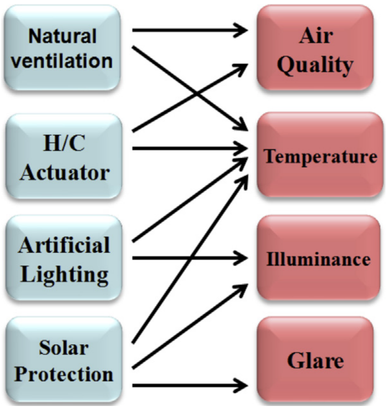

Fig. 1. Relationship of zone controllers and indoor comfort parameters.

more energy than the selected traditional non-integrated control strategies.

Here, we investigate the energy savings potential by applying an integrated multi-hour optimization for a five-zone office building. RC-network model of the building is used for optimization of dimmable light, blind position, inside air temperature, and outside air flow rate.

2. Methodology

2.1. Building thermal RC-network modeling

In order to develop a thermal network, it is necessary to subdivide the thermal system into a number of finite sub-volumes called nodes. The thermal properties of each node are considered to be concentrated at the central nodal point of each sub-volume. Each node represents two thermal network elements, a temperature (potential) and a capacitance (thermal mass).

The network elements are the resistance used to represent the heat transfer path from one node to another node. Conduction resistance is computed from the equation: $R = L/kA$. Convection resistance is computed from the expression: $R = 1/hA$ where A is heat transfer surface area, h is convection heat transfer coefficient, k is thermal conductivity and L is the wall thickness.

The conductive interaction in a multi-zone building can be modeled with simple RC-networks. In this formulation, the building is represented by a graph with nodes and resistance. A node may demonstrate a physical zone or point inside a wall. Resistance represents pathways for both conductive and convective heat transfer. The resulting model of the building consists of a large electrical network of resistors and capacitors (Fig. 2). For each zone conduction heat transfer from interior walls, exterior walls with thermal storage and windows with variable conductance (depending on shade position) is considered. Also indoor air heat gains from solar (q_s), artificial light (q_l), occupancies (q_i), outdoor air ventilation ($\mathrm{q_v}$), and heating and cooling ($q_{h/c}$) are considered.

2.2. Building and systems description

The prototypical building is a typical one-story office building with five zones. Details of building construction and systems are shown in Table 1. Roof and floor were assumed adiabatic for simplification. Each external wall has a shaded window with a wall to window ratio of 0.5 so that shading position affects conductance and transmittance coefficient of the window. Resistance values and solar heat gain from windows are changed linearly from open-shade to close-shade value. Occupancy and equipment schedule in addition to illuminance and heating and cooling set-points for occupied and un-occupied hours are shown in Table 2.

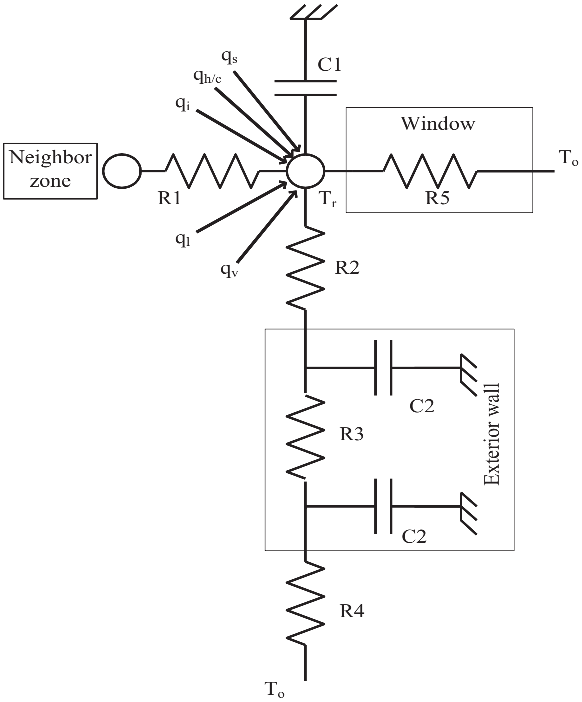

Fig. 2. RC-Network model of one zone. Variables are:C1: indoor air specific heat, C2: Exterior wall specific heat, R1: Interior wall R value, R2: Exterior wall indoor surface convection resistance, R3: Exterior wall R value, R4: Exterior wall outdoor surface convection resistance, R5: variable window conduction, R-value depends on shade position.

2.3. Optimization model components

2.3.1. Optimization variables and constraints

Based on a simplified RC-network modeling methodology, the five zones (four perimeters and one center zone) office building was modeled with (1) heat transfer, solar heat gain, and illuminance from window; (2) heat transfer from internal and external walls; (3) external walls heat storage; (4) internal heat gain from occupants and equipment; (5) ventilation rate; (6) cooling and heating systems load; and (7) illuminance and heat gain from artificial lights. This model was used for integrated optimization of HVAC and artificial lighting systems with non-linear programming method in MATLAB. Table 3 shows effective variables and disturbance of optimization problem. Variables X_1, X_2, X_5, and X_6 are independent control variables and the other variables are dependent variables that were calculated based on independent variables.

Table 1
Detail of building construction and systems.

Building parameters	Value
Chiller COP	3.5
Air specific heat (C1)	1 kJ/kg K (0.24 Btu/°F lb)
Electrical heater efficiency	1
Open shade window *U* value	2.3 W/m^2 K (0.4 Btu/h ft^2 °F)
Close shade window *U* value	1.4 W/m^2 K (0.25 Btu/h ft^2 °F)
Fluorescent lamp efficacy	70 lm/W
Exterior wall *U* value (1/R3)	0.4 W/m^2 K (0.073 Btu/h ft^2 °F)
Exterior wall specific heat (C2, C2)	42 kJ/kg K (10 Btu/ °F lb)
Exterior wall outdoor surface convection heat coefficient (1/R4)	34 W/m^2 K (6 Btu/h ft^2 °F)
Exterior wall indoor surface convection heat coefficient (1/R2)	8.5 W/m^2 K (1.5 Btu/h ft^2 °F)
Interior wall *U* value (1/R1)	1.53 W/m^2 K (0.27 Btu/h ft^2 °F)
Fan energy consumption	0.88 W (3 Btu/hr) per CFM of air
Maximum lamp power	15.8 W/m^2 (1.5 W/ft^2)