Applied Energy 204 (2017) 117–130

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Anti-logic or common sense that can hinder machine's energy performance: Energy and comfort control models based on artificial intelligence responding to abnormal indoor environments

Jonghoon Ahn *, Soolyeon Cho

North Carolina State University, Raleigh, NC 27695, USA

HIGHLIGHTS

- Integrated energy control model improves thermal comfort and mitigates an increase of energy consumption.
- Communication between heating and cooling, thermal comfort, and decision making models optimizes energy supply.
- PMV model effectively rectifies set-point temperature to reduce thermal dissatisfaction in various conditions.
- Five-step decision making model properly responds to abnormal situations derived from human anti-logic or common sense.
- Integrated model can be extended for managing risks caused by fire or disasters.

ARTICLE INFO

Article history:
Received 3 March 2017
Received in revised form 15 June 2017
Accepted 27 June 2017

Keywords:
Energy savings
Thermal comfort
Anti-logic
Common sense
Building control
Artificial intelligence

ABSTRACT

In spite of the remarkable development of technology, most studies for building energy controls to evaluate or estimate the energy performance have not accurately reflected actual building's energy consumption patterns. For this issue, several techniques, such as simulation and calibration, comprehensive survey system, smart metering, and commissioning, have been attempted.

However, in most studies, some factors in thermal systems derived from occupant behavior were perceived as fixed objects, and the factors were converted into simple numbers as parts of inputs into simulation templates. There was lack of studies on considerations that unpredictable responses derived from human anti-logic or common sense could deteriorate energy efficiency in theoretical analyses even though the systems were properly operated.

This research proposes integrated energy supply models based on artificial intelligence responding to anti-logic or common sense that can reduce machine's energy saving effects. By use of design scenarios assuming some unusual situations, a decision making model determines the extent to which the cause of the abnormal situations are associated with the occupant behavior. After the five-step phases in the decision making model, the actual outputs of the energy supply model for the buildings are determined, and the reciprocal communication between the thermal and decision making models mitigates thermal dissatisfaction and energy inefficiency. Comparative analysis describes the decision making model's effectiveness that it improves thermal comfort levels by about 2.5% for an office building and about 10.2% for residential buildings, and that it reduces annual energy consumption by about 17.4% for an office building and about 25.7% for residential buildings. As a consequence, the integrated energy control model has advantages that it noticeably improves thermal comfort and energy efficiency, and that it properly respond to abnormal and abrupt indoor situations derived from human anti-logic or common sense.

1. Introduction

1.1. Building energy control

For building thermal controls, several methods were developed to improve the performance of control systems. In addition to

---

* Corresponding author.
E-mail address: architectism@gmail.com (J. Ahn).

http://dx.doi.org/10.1016/j.apenergy.2017.06.079
0306-2619/

Nomenclature

A	area (m^2)
C_{res}	respiratory convective heat exchange
C_v	specific heat capacity at constant volume (J/kg·K)
C_p	specific heat capacity at constant pressure (J/kg·K)
clg	cooling
D	depth of envelope components (m)
E	error
ΔE	derivative of error
f_{cl}	ratio of clothed surface area to DuBois surface area
h_c	convection heat transfer coefficient (W/m^2·K)
h_{in}	specific enthalpy into room (J/kg)
h_{out}	specific enthalpy out from room (J/kg)
htg	heating
IAE	Integral (Sum) of Absolute Error
I_{clo}	clothing insulation (m^2·C/W)
k	transmission coefficient (W/m·K)
M	metabolic rate (W/m^2)
$\dot{m}_{ht}$	mass flow-rate from heater (kg/h)
$\dot{m}_{in}$	mass flow-rate into room (kg/h)
$\dot{m}_{out}$	mass flow-rate out from room (kg/h)
$m_{roomair}$	mass of room air (kg)
$q_{met,heat}$	metabolic rate subtracted by human work per unit Dubois surface area (W/m^2)
Q_{loss}	convection and transmission heat loss (J)
Q_{gain}	convection and transmission heat gain (J)
R	thermal resistance (m·K/W)
RH	relative humidity (%)
T_a	air temperature (°C)
T_{clo}	average surface temperature of clothed body (°C)
T_{ht}	air temperature entered into room (°C)
T_{out}	outdoor temperature
T_{room}	room temperature (°C)
T_{set}	set-point temperature (°C)
t	time
v_a	local mean air velocity (m/s)
u	internal energy (J)
W	work (J)
W_a	air humidity ratio
W_{sk}	saturated humidity ratio at the skin temperature

operation and maintenance strategies, many developments were made in components in thermal system such as fuel supply, valves and dampers, chillers and boilers, heat exchangers, and distribution parts. With the help of manufacturing technologies, optimized Heating, Ventilation, and Air Conditioning (HVAC) systems contributed to substantial improvement of energy efficiency, environmental protection, operation and maintenance, and economic aspects such as life-cycle and construction costs [1–5]. The Propor tional-Derivative-Integral (PID) algorithm including gain and threshold adjustment was, historically and commonly, used to improve the performance of plants, turbines, and building thermal systems [1,6–8]. Plant-level control systems have been typically preferred because of immediate and noticeable economic benefits by reduction of fuel costs. With rapid development of computing technologies, the performance of building control models was improved by adopting advanced statistical algorithms such as the Fuzzy Inference System (FIS) and Artificial Neural Network (ANN). The linguistic logics reflecting ambiguous expressions which cannot be defined as numerical values complemented mathematical and parametric controls, and conventional tuning algorithms based on experiments [9–11]. Through the strategy of combining PID and FIS models, some variations of control rules were tested to define control efficiencies of fuel use for boiler system and distribution networks in building cluster models [12,13]. The ANN model was the most beneficial to the rapid development of computer technology, which has made it possible to solve problems that have been difficult to even approach in the past because the number of cases increases exponentially with just a few variables. The ANN algorithm helped to solve day-lighting impacts on energy consumption, ventilation, air-conditioning, and radiant heat problems requiring analysis of large scaled data and numerous hidden interactions [14,15]. By means of mixing control algorithms, some advanced methods controlling valves or dampers were tested by combining experimental models and ANN algorithms to respond various demands at different geometry or climate conditions [16–18].

In order to improve thermal comfort level in buildings, some questionnaire-based researches were studied by means of various qualitative measurement systems based on users' characteristics [19,20]. In addition to subjective approaches for thermal comfort, mathematical Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) methods were used to combine various algorithms and the PMV model to define realistic thermal sensation rather than the rule based models [21,22]. In order to improve building control models to satisfy thermal regulations, several energy conservation measures were tested in simulations such as building envelopes including wall, door, and window, lighting, HVAC system associated with thermal comfort factors [23,24]. Some genetic algorithms to refine functions and tuning rules were adopted to develop FIS or ANN models with dynamic variables from co-simulation programs. Also, occupant responses obtained by comprehensive survey systems were analyzed to improve the performance of control rules and to reduce energy consumption [25,26].

However, despite the development of control technologies in diverse areas, there was still a significant difference between the actual building energy consumption measurement and simulation results, and a variety of approaches have been studied to solve the problem. Among them, calibration and commissioning are typically utilized as tools to find and amend some problems whether the building is well planned or is operating as intended after construction. Recent studies for calibration mainly dealt with automated methods even though all possible methods could be coupled to get better results. The automated method was mainly aimed at defining hidden interaction between energy conservation measures in real-time through a multi-layered hierarchical tree or matrix, and implementing more accurate simulation models [27–29]. Commissioning is also an useful technique, and it ensures that the new building operates initially as the owner intended and that building staff are prepared to operate and maintain its systems and equipment, so identifying the difference between building plans and actual energy consumption can be an important part of commissioning [30–32]. In order to complement a common lack of the study for human factors, precise sensing and measuring technologies should be the foundation, so smart sensors and meters have been developed and actually installed in many buildings. However, despite the application of such technologies, it was also pointed out that the patterns of energy consumption were largely influenced by user behavior patterns and their feedbacks [33,34].

1.2. Problem statement

In spite of several studies to control building energy system and measure the energy performance, there were few studies dealing