Applied Energy 154 (2015) 934–943

Contents lists available at ScienceDirect

Applied Energy

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

Energy efficient climate control in office buildings without giving up implementability

Mattias Gruber [a,b,*], Anders Trüschel [b], Jan-Olof Dalenbäck [b]

[a] ESBE AB, Bruksgatan 22, 33021 Reftele, Sweden
[b] Chalmers University of Technology, Energy and Environment, Building Services Engineering, Sweden

HIGHLIGHTS

- The principle of model-based controller for indoor climate control was adopted.
- A simplified version was presented and evaluated through experiments.
- A typical office working day was re-created in a test facility.
- Experiments were conducted for two weather seasons and two types of office rooms.
- Energy usage was reduced at the same time as the indoor climate was improved.

ARTICLE INFO

Article history:
Received 13 September 2014
Received in revised form 19 May 2015
Accepted 21 May 2015
Available online 10 June 2015

Keywords:
Office buildings
Indoor climate control
Implementability
Air-based heating and cooling
Energy efficiency
Model-based controller

ABSTRACT

The adaptation between a building and its automation system can potentially be increased by model-based controllers with an integrated control model and information about indoor climate disturbances. The associated energy savings potential is large but a widespread utilization is typically prevented by high complexities. From that point of view, a trade-off technology that combines implementability with an overall higher performance than the system of current practice would be a better option at most sites. This work presents an experimental evaluation of an alternative controller that follows the same principle as model-based, but has gone through a large number of simplification measures for a reduced overall complexity and a limited function. The controller was evaluated for indoor climate control by automating the ventilation flow rate during a typical office working day that was re-created in a laboratory environment. Experiments were conducted in two different office sites, as well as during two weather seasons of Swedish summer and winter. From the investigation, it was concluded that despite of the reduced complexity, the investigated controller could save between 12% and 19% of indicated energy compared to a system of common practice at the same time as the quality of indoor climate was maintained.

1. Introduction

A way of achieving cost- and energy efficient retrofits in buildings is to improve the building automation system (BAS). A high energy savings potential follows from that the BAS manages the operation of the HVAC (heating, ventilation and air-conditioning) system which in turn stands for approximately 76% of the total energy usage in European buildings [1]. At the same time, implementation of new BAS technologies is to a certain degree possible without major system changes, which means that installation costs can be small compared to the revenues.

As the BAS acts as an interface between the building and the HVAC system, the HVAC operation can be improved by increasing the adaptation to prevailing conditions by incorporating relevant information about building characteristics, the activities inside the building, the ambient climate etc. In this way, the necessary actions for achieving a desirable indoor climate from a static and dynamical point of view can be estimated before any deviations from desirable comfort regions occur. Also, the control activity could be planned ahead by anticipating future demands which opens up for the possibility of reducing energy usage by deciding on the most preferable actions. In its broadest sense, this technology is referred to as model-based control. A typical configuration

* Corresponding author at: ESBE, Bruksgatan 22, 33021 Reftele, Sweden. Tel.: +46 371878089.
E-mail address: mattias.gruber@esbe.eu (M. Gruber).

http://dx.doi.org/10.1016/j.apenergy.2015.05.075
0306-2619/

Nomenclature

c	CO_2 concentration (ppm)
c_p	specific heat capacity (J/(kg K))
$\dot{Q}$	thermal power (W)
t	Celsius temperature (°C)
u	controller input of thermal disturbances (W)
$\dot{V}$	volume flow rate (m^3/s)
y	controller output in ventilation flow quantities (m^3/s)

Greek letters

ρ	density (kg/m^3)

Subscripts

act	activation
adj	adjacent
s	supply
sp	setpoint
r	room

includes a sensing system that gathers information about indoor climate disturbances as exogenous inputs to an integrated control model. The control model is used to predict the corresponding impact on the controlled variables, and to adjust the HVAC control signals to achieve a desired behavior of the process, based on some given criterion.

Several previous works have indicated that model-based controllers can result in energy savings from about 20–50% without compromising comfort [2–6]. However, a typically high level of complexity means that implementation at most common sites are prevented along with a widespread utilization. Important aspects in this context are the number of disturbances considered as exogenous inputs, their quantifiability, how the associated information is processed by the control model as well as how input errors and deficiencies are compensated for. A complete correspondence between process and control model as well as information about all relevant indoor climate disturbances would potentially lead to a perfect adaptation between BAS and building. But, such controller is also associated to high installation costs, comprehensive commissioning as well as continuous maintenance to update for changes in the process. For that reason, extensive controller designs are unrealistic for considering in the majority of buildings.

Most previous works within the field of simplified model-based controllers have focused on finding control models that require less manual work than physical system representations, but still has the ability to predict the behavior of the indoor climate sufficiently accurate for a sufficient time ahead [7–12]. In [7], historical data from an office building was used to define a control model for predicting the indoor climate quality using HVAC power usage and weather as inputs. The model was furthermore validated by assessing the perceived indoor climate in the building and it was shown that the model-based controller could achieve energy savings between 19% and 32% compared to a baseline. In [8], a model-based controller with real-time flight schedules and electricity prices as inputs was investigated for temperature control in an airport. The considered control model was of grey-box type where a linearized physical representation was used as a starting point and an identification algorithm was applied together with historical data to capture nonlinearities and physical parameters through a process described in [9]. It was shown that the performance of the adapted control model was accurate enough to save 41% of the energy compared to a baseline control approach. Also [10] focused on a grey-box control model for predicting zone temperatures in an office building using forecast of outdoor air temperature, solar radiation, occupancy and internal heat gains as inputs. It was shown that the model could return accurate predictions over a horizon of two days and that the associated model-based controller led to energy savings of 17% compared to a conventional control system.

There are also some examples in literature on reducing the complexity associated to gathering and processing disturbances before used as exogenous inputs to the control model. Goyal [13] and Oldewurtel [14] et al. compared the benefits of utilizing future or present occupancy information as retrieved from prognosis or measurements, respectively, as inputs to model-based controllers for indoor climate control in office sites. The complexity aspect comes from that accurate forecasts typically require comprehensive models that are based on an extensive set of historical data while measurements can be generated in a more straight forward way. The results from the two studies were consistent and showed that measurements were sufficient for achieving energy savings around 50% in comparison to conventional controllers, while only small additional gains were provided through prognosis. Forecasts of indoor climate disturbances for control applications were also considered in [15] and [16], but with the focus on models for improving predictions. While [15] considered a self-tuning occupancy prediction model, [16] aimed to account for uncertainties in the control, and both investigations showed that their algorithms were beneficial.

Even though the cited works have showed that it is possible to reduce the complexity of model-based controllers without compromising performance, there are three reasons to why the proposed simplification measures cannot be considered as sufficient in typical building automation applications. First, complexity regarding control model and exogenous inputs were addressed individually which means that an overall low complexity could not be guaranteed. Second, complexity associated to gathering exogenous inputs were only investigated for a few examples (typically occupancy) and not for the entire set. Third, control or disturbance prediction models based on black- or grey-box algorithms might still be too complex since a large amount of training data is required in order to avoid a highly limited validity range [17]. In order to achieve a large scale implementation of model-based controller for indoor climate control, an overall low complexity is required. In turn, most simplification measures will have a negative impact on control performance. But in typical sites, a compromise between simplicity and performance is presumably sufficient, as long as a sufficiently high implementability can be combined with a considerable higher control performance than BASs of current practice.

1.1. Purpose and procedure

This paper contributes in the search for simple and energy efficient BAS by providing an experimental evaluation of an alternative controller that follows the same principle as a model-based but has gone through a large number of complexity reducing measures. This process was described in a previous publication [18] where the starting point was a controller with a complete energy