Energy and Buildings 75 (2014) 368–381

Contents lists available at ScienceDirect

Energy and Buildings

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

Evaluation and improvement of the energy performance of a building's equipment and subsystems through continuous monitoring

Ana Paula Batista [a,b,*], Maria Eugênia A. Freitas [b], Fábio G. Jota [a]

[a] Graduate Program in Electrical Engineering, Federal University of Minas Gerais, Av. Antônio Carlos 6627, 31270-901 Belo Horizonte, MG, Brazil
[b] Centre for Intelligent Energy Research, IERC, Federal Centre of Technological Education, CEFET-MG, Av. Amazonas 7675, 30510-000 Belo Horizonte, Brazil

ARTICLE INFO

Article history:
Received 17 March 2013
Received in revised form 7 February 2014
Accepted 8 February 2014

Keywords:
Building monitoring
Modelling
Control
Equipment

ABSTRACT

This study proposes an experimental method for the evaluation of a building's equipment and subsystems through the continuous monitoring of electrical and environmental process variables. The aim of the study is to improve the building's comfort and energy performance using an automatic control system. A case study of a building's air-conditioning system is presented using the proposed method. A dynamic equipment-control model for an artificially conditioned environment is described. Additionally, empirical models are developed that relate equipment variables, the conditioned environment and a building's surroundings and occupation characteristics using representation through transfer functions and auto-regressive models with exogenous inputs (ARX). The empirical models were created using continuous monitoring data via the Internet and a low-cost platform known as the end use monitoring centre (EUMC). These models represent the relevant characteristics of the involved variables in consideration of the complexity of the modelled phenomena. An automatic equipment control system was designed and installed. The systems resulted in significant improvements in comfort and energy efficiency. The proposed method can be applied to diverse types of equipment and subsystems in buildings.

1. Introduction

The understanding of process dynamics and the cause-and-effect relationships between relevant variables is necessary to evaluate and implement automation and control projects to improve the energy performance of a building's equipment and subsystems. Such equipment and subsystems are used to provide and control the illumination, environmental conditioning, water supply, safety, entertainment, and information technology in buildings. The use of elaborate and finely adjusted control strategies is one method to decrease the operational cost of such equipment while ensuring the quality of the processes involved (e.g., maintaining steady operations, comfort or security requirements with respect to temperature, humidity, luminosity and air-circulation or refrigeration settings). To justify the large investment that such equipment requires, it is essential to quantify the potential energy savings that can be achieved using such equipment. Thus, given the variety and complexity of the phenomena involved, it is necessary to establish cause-and-effect relationships and the lags between the translated variables, e.g., dynamic models that can represent the relevant characteristics of real processes. In [1], the influenced of time-lags between internal and external temperatures has been investigated, both experimentally and numerically, for different building envelope schemes.

The application of the optimal control strategy requires the evaluation of the operational variables (of the equipment and the environment), the energy consumption (of the equipment) and the manner in which the equipment and the environment are used through continuous monitoring. The variables with the largest influence on a building's energy performance according to the building's type [2], use and occupational characteristics [3] and the evaluated system must be selected and monitored.

Monitoring and automatic control technology plays an important role in the reduction of energy waste in various sectors, particularly in buildings [4]. Various case studies are found in the literature, such as those discussed below.

A general view of how monitoring and control system information can help reduce energy consumption in residences is presented by Meyers et al. [4]. The information obtained through monitoring systems enables the development of models that can establish

* Corresponding author at: Centre for Intelligent Energy Research, IERC, Federal Centre of Technological Education, CEFET-MG, Av. Amazonas 7675, 30510-000 Belo Horizonte, Brazil. Tel.: +55 31 3319 6765; fax: +55 31 3319 6763.
E-mail addresses: anapaula@des.cefetmg.br, anapaula.lcpi@gmail.com (A.P. Batista), mariaeugenia@des.cefetmg.br (M.E.A. Freitas), fgjota@ufmg.br (F.G. Jota).

http://dx.doi.org/10.1016/j.enbuild.2014.02.029
0378-7788/

the correlations between the relevant variables of the analysed processes as well as predict and record profiles of environmental variables and electrical energy demand, measure effective energy consumption, and identify equipment performance characteristics. An example of the use of predictive models to evaluate air-conditioning equipment is presented by Pereira and Mendes [5]. In their study, empirical models were created for four different types of air conditioner with the objective of predicting the total cooling capacity, the sensitive cooling capacity and the energy efficiency ratio (EER) for each piece of equipment.

Kim et al. [6] used monitoring data and proposed a prediction model for the indoor air quality (IAQ) of subway stations while considering, for example, the effect of seasonal temperature variations. Statistical methods, such as PCA (principal component analysis), were used to find the dependence between the different variables related to the IAQ, and regression methods (partial least squares – PLS) were applied to develop global and seasonal models. The results reflect the importance of considering the effect of seasonality on the models to improve precision.

Larsen et al. [3] used monitoring and simulation in a comparative study on consumption of gas and electricity in buildings. The authors compared real and simulated consumption, but the exact behaviour of the occupants (the presence and interaction of the users with the building) was unknown, or the actual indoor conditions were not monitored. Thus, the standard use and occupation schedules for a dry climate (of the Argentinean Northwest) were assumed.

In the case study evaluated in [3] (a two-story house inhabited by four individuals), the authors concluded that the simulations overestimated the energy consumption for heating and cooling, because, during the experiments, the use of heaters and coolers had been lower than the one predict in the simulations. The authors noted that is was unrealistic to assume that the building occupants in the case study were passive with respect to the indoor environment. Further, the models should be developed considering different countries and climates in order to be capable of adequately estimating the energy consumption. In [3], it is noted that improved predictions of a building's energy consumption and a better understanding of the relationship between the building and the users can be achieved using more complete user-behaviour models [3].

In recent years, substantial efforts have been made to improve energy efficiency in buildings, particularly in environmental conditioning processes, given that these processes represent a significant portion of the operational expenses. The equipment and subsystems required to provide a building's services consume a significant quantity of energy (approximately 40 quadrillion BTUs per year in the USA [7]), and among the sectors (residential, industrial and commercial), the final use that most significantly affects electrical energy consumption is refrigeration (refrigerator chambers, refrigerators, freezers and environmental conditioning). In the USA, the overall consumption for refrigeration represents 27% of the total [8], and in Brazil, this amount can be as much as 50% of residential consumption [9]. Refrigeration equipment possesses a substantial potential for saving energy and improving process quality (e.g., temperature fluctuation) and significantly contributes to energy consumption.

Analyses of the energy consumption and thermal characteristics of refrigeration systems have been performed recently experimentally [5,10] and through simulation [11–13]. Simulation depends strongly on the quality of the available models [11]. Qiao et al. [12] review methods and recent developments for modelling heating, ventilation and air-conditioning (HVAC) systems and tools for steady-state simulation. Koury et al. [13] propose two numerical models to simulate the transient and steady-state behaviour of steam compression refrigeration systems.

Additionally, various advanced control techniques applied to refrigeration systems have been studied in the literature [14–17]. In [14], an optimised on–off control strategy is proposed for application in refrigerated transport systems. A hybrid predictive control strategy proposed for application in a supermarket refrigeration system is presented in [15]. Huang et al. [16] propose a robust predictive model-based control strategy for application in air conditioning systems. A comparison between robust H_∞ controllers and pole placement applied to an air-conditioning system is presented by Moradi et al. [17]. Advanced control techniques, such as, for example, model-based predictive controller, have also been applied in conjunction with BEMS (Building Energy Management Systems) so as to achieve optimum indoor environmental conditions while minimising the energy costs [18].

In the present study, a method is proposed for the evaluation and improvement of the performance of a building's equipment and subsystems through monitoring, modelling and continuous control using a low-cost platform known as the end use monitoring centre (EUMC) in which the quantities of interest can be measured and the control actions performed via the Internet. These quantities can be visualised in real time or stored in a database for later use. As a result of the influence of stochastic variables, certain physical properties and unknown parameters, the proposed method proposed uses empirical models based on long-term measurements (months) that are derived from the continuous monitoring of electrical, environmental and process variables.

With continuous monitoring of the electrical, environmental and process variables, correlations can be established between electrical energy consumption and the variables of interest, such as the thermal load on refrigeration systems, and apply advanced control techniques to temperature-conditioning systems to reduce energy consumption and obtain smaller temperature oscillations. To adjust the relevant controllers and enable the evaluation of the gains achieved by implementing the control strategies, it is essential that the dynamic models can satisfactorily represent the real behaviour of the processes. To create representative models, it is necessary to perform measurements and conduct a global analysis for long periods (days, months or years). Given the large variety of operating conditions (e.g., the load to which the system is subjected, seasonal variations and climatic instability), the conclusions drawn from short duration tests (i.e., a few hours) generally cannot be extrapolated to other circumstances, even if the other circumstances appear to be similar.

In this study, the air-conditioning system of a small auditorium was investigated as a case study. However, the proposed method is equally applicable to diverse equipment and subsystems in a building, since that each subsystem is realistically characterised. In the following sections, the proposed method, the platform and the case study are described. Details are provided with respect to the environment, the monitored variables, the dynamic models and the relationship between the monitored variables. An automatic control system for the air-conditioning equipment was installed and a significant reduction in energy consumption and an improvement in thermal comfort were obtained. Additionally, an analysis of the gains achieved with the implemented control system is presented.

The work, carried out with real data, indeed confirms that, only by monitoring for long periods of time, it is possible to systematically evaluate the behaviour of the relevant variables that have long-term influence. Nevertheless, after getting a model that can be continuously improved over time with data of long periods, it is possible to automatically retune the controller adaptively to increase the gains achieved over time. But the study also shows that, even with simplified models, it is possible to have significant energy gains (in the order of 20%) and improvements in the quality of control (which justifies the implementation of the automatic control systems properly designed and tuned, using short-term models).