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Assessing thermal comfort and energy efficiency in buildings by statistical quality control for autocorrelated data

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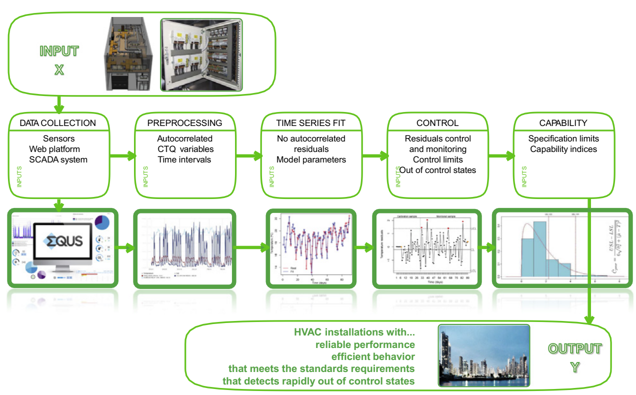
HIGHLIGHTS

- Intelligent web platform development for energy efficiency management in buildings.
- Controlling and supervising thermal comfort and energy consumption in buildings.
- Statistical quality control procedure to deal with autocorrelated data.
- Open source alternative using R software.

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, a case study of performing a reliable statistical procedure to evaluate the quality of HVAC systems in buildings using data retrieved from an ad hoc big data web energy platform is presented. The proposed methodology based on statistical quality control (SQC) is used to analyze the real state of thermal comfort and energy efficiency of the offices of the company FRIDAMA (Spain) in a reliable way. Nonconformities or alarms, and the actual assignable causes of these out of control states are detected. The capability to meet specification requirements is also analyzed. Tools and packages implemented in the open-source R software are employed to apply the different procedures. First, this study proposes to fit ARIMA time series models to CTQ variables. Then, the application of Shewhart and EWMA control charts to the time series residuals is proposed to control and monitor thermal comfort and energy consumption in buildings. Once thermal comfort and consumption variability are estimated, the implementation of capability indexes for autocorrelated variables is proposed to calculate the degree to which standards specifications are met. According with case study results, the proposed methodology has detected real anomalies in HVAC installation, helping to detect assignable causes and to make appropriate decisions. One of the goals is to perform and describe step by step this statistical procedure in order to be replicated by practitioners in a better way.

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1. Introduction

The development of energy platforms and statistical methodologies to control and supervise heat, ventilation and air conditioning (HVAC) installations is now absolutely necessary in order to obtain higher control, lower energy consumption, and, as a result, to decrease the overall expenditure in buildings. Today, the optimization requirements concerning the use of climate systems in buildings are due to their increasing energy consumption. In fact, energy consumption in buildings raise up to 50% of overall energy generation in countries such as USA (including the cost of heating and refrigeration), where the consumption of climate systems is about 20% of the total [1,2].

The increasing need of reducing energy consumption in buildings has accelerated the development of new energy optimization systems. They are based on the implementation of different techniques and technologies concerning engineering, computer science, and statistics. Recently, the application of consumption optimization systems has been effective in terms of energy savings [3,4]. In the last decade, many different methods using artificial intelligence approaches [5–8], and specifically genetic algorithms [9,10] have been applied to perform consumption prediction tasks in HVAC systems. Moreover, also stochastic and other mathematical methods have been developed to make predictions of climatic variables [11–15], energetic variables [16], savings [17], and to perform control and automated systems to increase the effectiveness and energy savings [15,18,19].

Nowadays, the number of datasets composed of autocorrelated variables is continuously increasing due to advances in sensoring, computer science and database management. Accordingly, the current state of the art related to time-dependent data forecast is also growing up. Since the introduction of the Box-Jenkins methodology [20], widely known for modeling and forecasting time series, a great amount of valuable works dealing with interesting applications in different fields such as agricultural science, social sciences, engineering or environmental science [21–24], showing its great performance, have been published. In fact, an important goal of the present work is just to achieve more accurate estimates of the temperature and energy consumption variability due to common causes by using a seasonal autoregressive integrated moving average (seasonal ARIMA) model, which depends on the so-called the Box-Jenkins methodology. As a consequence, the process to control, detect anomalies, analyze and enhance the quality of thermal comfort is improved. It is also important to mention that, the lack of nonlinear modeling capability of Box-Jenkins methodology has triggered the development of other techniques for the purpose of time series forecasting. That is the case of the use of artificial neural networks (A-NN), that accounts for nonlinear effects. In that sense, from a forecasting perspective, A-NN models have been extensively used in many applications where their performance have been compared with the Box-Jenkins methodology, and also with respect to hybrid models based on both techniques [23,25]. Considering that the present study also deals with anomaly detection, it is interesting to stress that A-NN have been applied for this task, specifically, in the case of alarm detection concerning drought years and wet years [26], in agricultural science. In the present work, seasonal ARIMA models are applied taking into account that, in the framework of statistical quality control (SQC), the Box-Jenkins time series modeling is recommended when working with autocorrelated data [27]. The aim is to control the thermal comfort and energy efficiency in buildings, to estimate the natural variability of temperature and energy consumption in some period, and then detecting patterns and system anomalies if they are produced. All this preventing the over fitting of time series variation due to assignable causes, which are changes related to HVAC system anomalies. In addition, as explained below, the proposed methodology provides an statistical procedure based in control charts to analyze the time series residuals, to estimate natural variability, and to detect anomalies.

This study aims to control (detecting alarms) and improve the quality of HVAC systems by implementing SQC tools. This is done overcoming the problem of working with strongly autocorrelated variables. In fact, critical to quality (CTQ) variables in HVAC systems retrieved from sensors are often autocorrelated. They depend on weather, environmental conditions and human activity that is subjected to routine timetables [28–33]. Woodall and Montgomery [27,34,35], among others, have been discussed about the challenge of estimating quality control limits of autocorrelated data. Considering that autocorrelation usually leads to an increase in process variability [34], one of the most recommended actions to deal with this type of data is to remove the source of autocorrelation by fitting Box-Jenkins time series models [20,27,34,36–39]. Since the autocorrelation is extracted, the next step is to control the process performance by Shewhart, exponentially weighed moving average (EWMA) or cumulative sum (CUSUM) control chart to time series model residuals [20,27,38,40] There are other alternatives such as the implementation of moving center line EWMA chart (assuming ARIMA(0,1,1) autocorrelation model) with control limits based on prediction error variance, and the model-free batch mean control chart [27]. Many other alternatives such as modified Shewhart, EWMA and CUSUM charts are summarized in [41] where different Box-Jenkins models are assumed, mainly AR(1) and ARMA(1,1). It is important to note that if the control process performance deals with autocorrelated data and usual control charts are applied (assuming independent, identically distributed process), a great amount of non-informative out-of-control signals will be detected.

There are some valuable works that apply statistical procedures to detect alarms in HVAC systems through CTQ variables monitoring [29,31–33]. In Wang et al. [29], AR(1) time series models are applied to Δ(temperature-target) and their residuals are controled and monitored by CUSUM control charts. Zhao et al. [31] propose the application of a support vector regression algorithm (instead time series model) to the reference performance index models. The process is controlled by applying EWMA control charts to model residuals. Sallans et al. [32] introduce a new method based on maximum likelihood procedure to detect alarms. Moreover, a method based on EWMA application to analyze sensitivity and uncertainty for HVAC optimal control strategies is provided by Shan et al. [33]. As pointed out, many studies assume AR(1) and ARMA(1,1), nevertheless the dependence structure of CTQ variables in HVAC systems is often complexer. Thus, in order to obtain independent and equally distributed residuals, to fit complexer ARIMA models is many times necessary. This is one of the goals of the present work.

Further capability analysis application is many times necessary and useful to evaluate the installation performance [27,42]. Capability analysis allows to verify if the HVAC system meet the standard specifications requirements (and to what extent). When working with autocorrelated CTQ variables, the hypothesis observation independence is not met, thus the application of modified capability index for autocorrelated data is required [28,43,44]. This work introduce new modified capability indices in HVAC control and energy efficiency domain, previously developed for environmental applications [28].

From a computational statistics perspective, this work provides free statistical tools to implement the proposed methodology devoted to control the performance and detect alarms in HVAC systems. `R` software [45] is now the most comprehensive and flexible