



Multivariate statistical monitoring of buildings. Case study: Energy monitoring of a social housing building



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ABSTRACT

A complete methodology for energy building monitoring based on Principal Component Analysis (PCA) is proposed. The method extends the Unfolding or Multiway Principal Component Analysis (MPCA) used in statistical batch process control in terms of building and neighbourhood monitoring. Relationships between energy consumption and independent variables such as weather, occupancy or any other variables that are significant for monitoring can be gathered in a model using the proposed methodology. Historic data are used to obtain a reference model that will be used for monitoring. Two unfolding strategies are proposed (time-wise and entity-based) offering complementary views of the building or of the community under consideration. The first, time-wise unfolding, is suitable for detecting behavioural changes over time, whereas entity-wise unfolding allows the identification of entities, e.g. dwellings in a building, that behave substantially differently from others over a period of time. Two simple statistics, T^2 and SPE , are used to define two monitoring charts capable of detecting abnormal behaviours and, furthermore, the isolation of variables that mainly explain such a situation. The paper presents the theoretical background, followed by the methodological principles. The results are illustrated by a case study.

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1. Introduction

Nowadays, residential and commercial buildings account for around 40% of final energy use and are responsible for 36% of the European Union's total CO₂ emissions. In order to reduce energy consumption, great efforts are being made to develop and apply European directives [1] that act as an incentive with regard to the efficient use of energy, and the better performance of buildings. However, a gap still exists in the area of energy monitoring in terms of facing the challenge of understanding how energy is being consumed, identifying major loads and losses, and discovering relationships between energy consumption and the activities performed by users. Enhanced monitoring methods, providing significant information that is useful in terms of understanding energy consumption patterns, are required to perform cost-effective analyses of conservative measures, identify irregularities, and help to define and evaluate the new design

requirements of buildings. Energy measuring and monitoring is an essential aspect of understanding energy uses, and assists energy management activity supporting decision making based on quantitative and objective information. Thus, the enhancement of actual energy monitoring systems is necessary, and they have to evolve towards systems capable of exploiting information contained in the variety of data being collected by building management systems (BMS) and other data acquisition systems installed in buildings, facilities and/or neighbourhoods, such as weather stations, wireless sensors networks (WSN) or access control systems, among others.

The purpose of this paper is to propose a general methodology to automatically build data-driven energy models capable of exploiting the information contained in data records being collected with regard to a building (or a neighbourhood) during normal operational conditions, and exploit it as part of the monitoring tasks to evaluate changes in energy consumption behaviour. Thus, a model representing the normal operational conditions of a building can be easily used to detect and diagnose deviations from the modelled behaviour (faults, over-consumption, efficiency losses, etc.) or to evaluate the effectiveness of energy conservation measures. The work aims to extend the methodology not only to buildings but also to consider communities (residential buildings, social buildings and neighbourhoods, for example) by gathering information about

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possible relationships in the variables being monitored. The energy demands of a central heating system can be influenced by both the weather conditions and by individual household occupancy, for example. The idea is to take advantage of multivariate techniques, as used in the process industry, and adapt them to building energy monitoring. Thus, a modelling approach has to gather information about the relationships that exist between consumption and weather or occupancy, but also with regard to dependencies that exist with other variables and factors that can affect energy consumption. According to [2] the main factors influencing energy consumption in buildings can be divided in seven categories:

- Climate
- Building characteristics
- User characteristics
- Building services
- Building occupant's behaviour and activities
- Social and economic factors
- Indoor environmental quality requirements

The proposed method has to be able to deal with observation vectors describing the variables and factors related to these seven areas. Since the number of variables to be included in the model could be large, a method capable of identifying correlations among variables and, at the same time, compressing redundant information into lower dimensional spaces, is required. Principal Component Analysis (PCA) has been selected to deal with the trade-off between dimensionality and complexity, because of its solid theoretical principles and its adequacy in terms of problem formulation. A particular extension known as Unfold Principal Component Analysis (Unfold PCA) or Multiway Principal Component Analysis (MPCA), commonly used in batch process industries [3], has been studied and adapted for modelling and monitoring energy consumption in buildings. This selection is based on the fact that buildings usually are operated following pseudo-periodic patterns (e.g. daily, weekly patterns) and interest resides in analysing such patterns and dependencies, with variables being monitored during the building operation period, instead of considering only instantaneous relationships. Moreover, the method considers the existence of interdependencies among multiple entities (i.e. dwellings or buildings), that allows the extension of the method to the monitoring of residential buildings composed of multiple dwellings or to a neighbourhood.

PCA is a projection technique that allows the representation of dependencies among variables in a lower dimension space defined by orthogonal components. Thus, the method gathers information about relationships among variables in this projection space in terms of correlated information, whereas non-correlated information falls in the residual space. Two statistics – Hotelling's T^2 , and SPE (square prediction error) – defined in those subspaces in the form of projection and residual spaces, respectively, are used to model the adequacy of the new data with respect to the PCA model (obtained from historical data). Thus, large deviations of these statistics (over a statistical threshold) are used to detect emergent behaviours when monitoring new observations. Moreover, when this happens, the proposed methodology allows the identification of the variables responsible for such large variation by applying contribution analysis. The adaptation of these statistical principles allows the enhancement of energy monitoring systems with the following capabilities:

- Description of dependencies among energy consumption and other monitored variables.
- Detection of faults in sensors and the reconstruction of sensor readings when data are missing or corrupted.
- Rapid detection of emergent behaviour.

- Forecasting of energy consumption based on independent variables.
- Robust monitoring, in the presence of data errors or missing values.
- Creation of simple control charts to monitor multiple variables at a glance.
- Rapid identification and isolation of variables involved in abnormal consumption patterns.
- Modelling of relationships among dwellings in residential buildings or neighbourhoods.

In the next section, a review of the state of the art introduces the interest in this field. The paper follows with a description of the PCA background in terms of modelling and monitoring, including fault detection and diagnosis capabilities. Then, the Unfold-PCA extension is considered, emphasizing how different unfolding strategies can be used to offer different monitoring views of a building or of a neighbourhood. Finally, a case study focusing on energy monitoring of social buildings is presented to illustrate the benefits of the approach.

2. Related works

This section illustrates the interest in data-driven modelling, and how these paradigms can be used to extend energy monitoring capabilities. The section does not pretend to cover all the methods described in the literature, but focuses on those that contributed to a definition of new energy monitoring paradigms for buildings. Building energy modelling methodologies can be categorized [4] in terms of two big groups: top-down and bottom-up methodologies. Top-down modelling techniques start from the analysis of energy consumption and do not try to detail causes or end-uses. They mainly focus on the cause-effect relationship between long persistent changes (in buildings or neighbourhoods) and with regard to consumption. On the other hand, bottom-up approaches are generally based on the identification of contributions related to energy end-uses in order to build an aggregated energy model. Two distinct strategies can be differentiated in this second group: statistical (or data-driven) and engineering (or based on first principles) approaches. An extended review of techniques addressing both approaches for building energy modelling can be found in [5] and [6]. Table 1 briefly summarizes the general weaknesses and strengths of each group of techniques.

Modelling is essential for energy monitoring, since it increases system knowledge and allows the establishing of the reference model required for any assessment task. Particular cases addressing the monitoring of large public buildings are studied in [7]. Methodologies to improve the adjustment and calibration of tools to support monitoring are studied in [8] and a solution based on evidences is proposed in [1]. Energy efficiency models for urban environments and buildings are usually calibrated with hourly data [9] and typologies of days and seasons are used to introduce corrections. Recently, modelling improvements have been supported by the deployment of wireless sensors (i.e. [10]). In this context, case studies analysed in [11] have served to offer recommendations when monitoring energy performance in buildings. On the other hand, the use of Principal Component Analysis (PCA) is not new in this area; however the way in which it is used differs substantially from the method proposed in this paper. Thus, PCA has been proposed simply as a reduction technique in [12] dealing with dwelling energy data, air-handling units [13], chilling plants [14], or for human activities' outlier detection [15]. PCA has also been proposed for clustering in the heating evaluation of school buildings [16], applied as a feature selection technique in [17] or to analyse seasonal variations in electricity use in office buildings [18].

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