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Energy consumption control automation using Artificial Neural Networks and adaptive algorithms: Proposal of a new methodology and case study

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HIGHLIGHTS

- A methodology to enable energy consumption control automation is proposed.
- The methodology is based on the use of Artificial Neural Networks.
- A method to control the accuracy of the model over time is proposed.
- Two methods to enable automatic retraining of the network are proposed.
- Retraining methods are evaluated on their accuracy over time.

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ABSTRACT

Energy consumption control in energy intensive companies is always more considered as a critical activity to continuously improve energy performance. It undoubtedly requires a huge effort in data gathering and analysis, and the amount of these data together with the scarceness of human resources devoted to Energy Management activities who could maintain and update the analyses' output are often the main barriers to its diffusion in companies. Advanced tools such as software based on machine learning techniques are therefore the key to overcome these barriers and allow an easy but accurate control. This type of systems is able to solve complex problems obtaining reliable results over time, but not to understand when the reliability of the results is declining (a common situation considering energy using systems, often undergoing structural changes) and to automatically adapt itself using a limited amount of training data, so that a completely automatic application is not yet available and the automatic energy consumption control using intelligent systems is still a challenge.

This paper presents a whole new approach to energy consumption control, proposing a methodology based on Artificial Neural Networks (ANNs) and aimed at creating an automatic energy consumption control system.

First of all, three different structures of neural networks are proposed and trained using a huge amount of data. Three different performance indicators are then used to identify the most suitable structure, which is implemented to create an energy consumption control tool. In addition, considering that huge amount of data are not always available in practice, a method to identify the minimum period of data collection to obtain reliable results and the maximum period of usability is described. The general purpose of the work is to allow the automatic utilization of this kind of tools, so a method to identify a lack of accuracy in the model and two different retraining methods are proposed and compared (Mobile Training and Growing Training).

The whole approach is eventually applied to the case study of a tertiary building in Rome (Italy).

1. Introduction

Over the last years energy management has gained an always more prominent role in performance controlling and

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competitiveness improvement efforts of any company. The importance of energy management is enhanced by three main drivers: the growing energy costs, the always more restrictive environmental regulations (also introducing additional costs related to CO_2 emissions), and finally the "green" customers' purchasing behaviour as regards products and services [1,2]. Energy management systems are consequently gradually being introduced in many companies, together with information systems assisting data gathering activities, which are one of their main pillars [3]. In fact, measuring and controlling energy consumptions are essential activities to accomplish the objectives of reducing energy wastes and raising energy efficiency awareness, and Internet of Things technologies are nowadays fostering these activities, making a huge amount of data easily available for analyses. Thus, there is a substantial need of methodologies and tools that enable simplified energy performance measurement and analysis and consumption control [3,4].

For all these reasons, an energy consumption control system is nowadays an indispensable tool for any energy intensive company [5]. These systems are in fact able to identify a reliable energy consumption baseline and to compare actual consumption values with it, allowing energy managers to evaluate performances, identify malfunctions or energy efficiency opportunities and promptly undertake corrective actions [6]. Moreover, after an energy efficiency project is concluded, a control system can be used to compare previous to current consumptions, calculating the obtained energy saving [7].

Anyway controlling over time the energy behaviour of complex systems (i.e. systems presenting highly variable consumptions and a huge number of drivers influencing energy performance, and also requiring a high frequency data update to make the control over time effective) can be quite difficult and time consuming, and might require a huge effort [6,8,9]. Statistical definition of energy baseline is often required [10] and these kind of models have to be constantly updated and maintained, verifying their accuracy at fixed intervals (energy using systems often undergo structural changes and dramatic configuration modifications, and baseline models' validity might fall [11]). In addition, considering multi-site companies, generally characterized by a huge number of buildings or energy systems to be managed by a centralized Energy Management Office with no or partial knowledge of their actual configurations and unaware of possible ongoing modifications, the work can become even heavier. Thus, automation can play a significant role in simplifying these activities and enhancing the diffusion of energy control systems.

To this purpose Artificial Neural Networks, self-learning tools that are able to approximate nonlinear relationships between input and output variables of complex systems [11], can be undoubtedly taken into account. They have already been often implemented to characterize energy systems' behaviour, as next paragraph will demonstrate, but entail two main criticalities when it comes to energy consumption control automation: the huge amount of historical data that is required in order to create a reliable baseline model is not often available (the introduction of information systems in the energy management field is still an ongoing, incomplete activity) [11–16], and even when it is available the probability that changes occur to the system and therefore that the baseline model becomes poorly accurate after a short time is high [11,13,15–20]. In particular, the identification of a lack of accuracy in the baseline model is of particular interest in energy consumption control system, as it allows distinguishing between a real energy waste (anomalous energy behaviour) and a simple maintenance need of the control system itself.

In the present paper, a new methodology to overcome both criticalities and automate energy consumption control is proposed. Artificial Neural Networks are used to allow an easy complex systems' modelling, and performance indexes are compared to choose the best network's structure. An adaptive algorithm is proposed to allow an automatic identification of lack of accuracy in the model (retraining need) and two different retraining methods (mobile training and increasing training) are presented and compared even in terms of their reliability over time. When a lack of accuracy appears (for example after a structural change is made to the system), retraining methods are used to allow keep on effectively monitoring the efficiency of the system even without having a huge amount of data (or more reliable data referred to similar seasons) to set the baseline. Eventually, in order to make the proposed methodology as widely applicable as possible, a method to identify the minimum period of data collection to obtain reliable results and the maximum period of usability is described, considering that huge amount of data are not so often available in practice.

The outcomes of this methodology (in terms of ANN's structures, accuracy control method and retraining methods) are meant to allow an easy creation and automatic maintenance over time of energy consumption control systems so as to foster their spread even where they had not yet been implemented, and so helping the energy waste reduction, the individuation of possible energy efficiency opportunities and the raise of energy efficiency awareness in any sector. The methodology and tools proposed can be applied to any energy consuming system and used to build automatically updatable control tools such as deviations charts and CuSum charts [5,6].

The whole approach is eventually applied to the case study of a tertiary building in Rome (Italy), which represents a perfect example of a complex system whose energy consumptions are variable according to several drivers and is likely to undergo several structural changes over time.

2. Background

2.1. Approaches to the characterization and prediction of energy consumption for complex systems

Different approaches to energy consumption modelling, forecast and control of complex systems are available in literature. Energy characterization models can be classified basing on the methods and tools used to develop them.

First of all, it is possible to distinguish between engineering approaches and data-driven approaches [21–23], see the schematic representation given in Fig. 1.

Engineering approaches use physical and thermodynamic functions to exactly derive theoretical energy consumption of processes and systems; they produce accurate results but also require detailed inputs [21,24]. They can be further divided into simplified and elaborate approaches basically according to the number of equations and variables considered in the model.

Data-driven approaches, instead, use historical data to individuate the relation between energy consumption and its drivers (hereinafter called energy drivers) [21–29]. They can be structured as a "white-box" [23,25,29] if the individuated relation is mathematical and explicitly given in the form reported in Eq. (1):

$$E = E_0 + f_1(x_1) + f_2(x_2) + \ldots + f_n(x_n) \quad (1)$$

(where E represents the total energy consumption, E_0 the constant portion of the energy consumption, f_i the portion of the energy consumption which is variable according to the energy driver x_i) or as a "black-box" if the relation is not clearly explicit (they predict the value of energy consumptions basing on input variables' values). Black-boxes are typically created using machine learning techniques such as Artificial Neural Networks (further discussed in the followings) or Support Vector Machines [26,27,29], or by the means of Decision trees [23,28].