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Fault detection analysis using data mining techniques for a cluster of smart office buildings

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ABSTRACT

There is an increasing need for automated fault detection tools in buildings. The total energy request in buildings can be significantly reduced by detecting abnormal consumption effectively. Numerous models are used to tackle this problem but either they are very complex and mostly applicable to components level, or they cannot be adopted for different buildings and equipment. In this study a simplified approach to automatically detect anomalies in building energy consumption based on actual recorded data of active electrical power for lighting and total active electrical power of a cluster of eight buildings is presented. The proposed methodology uses statistical pattern recognition techniques and artificial neural ensembling networks coupled with outliers detection methods for fault detection. The results show the usefulness of this data analysis approach in automatic fault detection by reducing the number of false anomalies. The method allows to identify patterns of faults occurring in a cluster of bindings; in this way the energy consumption can be further optimized also through the building management staff by informing occupants of their energy usage and educating them to be proactive in their energy consumption. Finally, in the context of smart buildings, the common detected outliers in the cluster of buildings demonstrate that the management of a smart district can be operated with the whole buildings cluster approach.

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1. Introduction and background knowledge

Buildings are becoming more and more complex energy systems consisting of several elements i.e. heating/cooling systems, ventilation systems, lighting and control systems etc. In addition, buildings have multifarious activities and the occupants may have different demands from a building. Even though building ramification is growing, communication between the participants and the building elements during the building life is poor (Djuric & Novakovic, 2009). The building energy system and the monitoring of its energy and environmental performance has been the subject of great interest in recent years. There is an increasing awareness that many buildings do not perform as intended by their designers. Typical buildings consume 20% more energy than necessary due to faults occurring at a different level of the building life cycle i.e. from construction to operations (Song, Liu, Claridge, & Haves, 2003; Wu & Sun, 2011). The building energy management system (BEMS) collects and stores massive quantities of energy consumption data. The goal of BEMS (control of energy uses and costs, while

maintaining indoor environmental conditions to meet comfort and functional need) cannot be achieved without uncovering valuable information from the tremendous amounts of available data and transform it into organized knowledge (Djuric & Novakovic, 2009). Hence significant potential exists for better use of BEMS data through fault detection analysis in order to improve operations and save energy.

Fault detection is the determination that the operation of a building is incorrect or unacceptable from the expected behavior (Haves, 1999). Research on fault detection and isolation in automated processes has been active over several decades. A number of methodologies and procedures for optimizing real-time performance, automated fault detection and fault isolation were developed in the IEA ECBCS Annex 25 (Liddament, 1999). Many of these diagnosis methods are later demonstrated in real buildings in the IEA ECBCS Annex 34 (Jagpal, 2006), which focused on computer-aided fault detection and diagnosis. Annex 40 (Visier et al., 2005) encompasses commissioning process, building control system, component level models, simulation models at the building level for commissioning. The Executive Committee for the same implementing agreement published Annex 47-report 4 (Akin, 2010) on the use of flow charts and data models in the practice

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and research of initial commissioning of advanced and low energy building systems in order to improve their operating performance.

Many fault detection and diagnosis (FDD) tools are based on combinations of predicted building performance models and a knowledge-based system. They compare the performances of all or part of the building over a period of time to what is expected, in this way incorrect operation or unsatisfactory performances can be detected. The expected performances can be assumed, desired and model-based (Djuric & Novakovic, 2009). Early attempts at displaying energy consumption data for the energy optimization involved the use of graphs to inform the user on the trends within their building systems (Claridge, Haberl, Sparks, Lopez, & Kissock, 1992; Haberl & Abbas, 1998 I, 1998 II; Haberl, Sparks, & Culp, 1996; Prazeres & Clarke, 2003). The graphical indices can be used to analyze building energy consumption data and to check for errors, but they are usually laborious. Katipamula & Brambley (2005 part I and part II) classified the FDD methods for building energy systems and highlighted the strength and weakness of each approach. Most of the research related to FDD focused on the component-level faults (Du, Jin, & Yang, 2009; Han, Cao, Gu, & Ren, 2010; Wang & Xiao, 2004; Zhao, Wang, & Xiao, 2013), and few researchers (Yu & Dolf, 2003; Dodier & Kreider, 1999; Holcomb, Li, & Seshia, 2009; Li, Bowers, & Schnier, 2010) discussed the FDD strategy for whole building lighting and HVAC systems energy consumption.

The pattern recognition-based methods, which belong to the history-based methods category (Katipamula & Brambley, 2005 part I), are advantageous for fault detection since they do not require a deep understanding of physics of the concerned system(s) and can be applied to different levels. Seem (2005) proposed a pattern recognition algorithm for automatically determining the days of the week with similar energy consumption profiles. Seem (2007) also presented a method for converting the energy consumption data into information and accounted for weekly variation in energy consumption by grouping the days of week with similar power consumption. Liu, Chen, Mori, and Kida (2010) classified the building lighting power data considering the number of people and then implemented a robust statistical algorithm to detect the outliers. Fontugne et al. (2013) used the Strip, Bind and Search (SBS) method to build sensor traces in order to identify abnormal device usage in buildings.

In the recent years the application of artificial intelligence (Palade & Bocaniala, 2006; Patton, Lopez-Toribio, & Uppal, 1999) became one of the most important topics in fault detection. Chen, Wang, & van Zuylen (2010) described the density based local outlier approach and compared it with two further algorithms, the statistics-based approach and the distance-based approach, for detecting and analyzing the outliers in traffic data sets for an application to intelligent transportation systems. The experimental results reveal that this method of outlier mining is feasible and more valid than the other two methods presented to detect outliers. Cao, Si, Zhang, and Jia (2010) proposed a density-similarity-neighbor-based outlier mining algorithm for the data preprocess of data mining technique. They performed the experiments on synthetic and real datasets to evaluate the effectiveness and the performance of the proposed algorithm; the results verified that the proposed algorithm has a higher quality of outlier mining and do not increase the algorithm complexity. Chen, Miao, & Zhang (2010) introduced a neighborhood-based outlier detection algorithm that integrates rough-set-granular technique with the outlier detecting. The experimental results show that neighborhood-based metric is able to measure the local information for outlier detection. The detected accuracies based on the neighborhood outlier detection are superior to the k-nearest neighbor for mixed dataset, and a little better than recurrent neural network for discrete dataset. Alan and Catal (2011) proposed an

outlier detection approach using both approaches software metrics thresholds and class labels to identify class outliers. The experiments revealed that their novel outlier detection method improved the performance of robust software fault prediction models based on Naive Bayes and Random Forests machine learning algorithms. Razavi-Far, Zio, and Palade (2014) focused on the development of a pre-processing module to generate the latent residuals for sensor fault diagnosis in a doubly fed induction generator of a wind turbine. The inputs of the pre-processing module were batches of residuals generated by a combined set of robust observers to operate point changes. The outputs of the pre-processing module were the latent residuals progressively fed into the decision module, a dynamic weighting ensemble of fault classifiers that incrementally learned the residuals-faults relationships and dynamically classified the faults including multiple new classes. The results of simulations confirmed the effectiveness of the approach, even in the incomplete scenarios due to sensor failures.

Many theoretical studies in the application research of artificial intelligence are focused on artificial neural networks (ANNs) (Haykin, 1999; Kosko, 1992) and a large number of papers on the application of ANNs for FDD have been published. Arseniev, Lyubimov, and Shkodyrev (2009) provide an approach for building the FDD system based on the ANNs and an automatic training method for such systems. The paper shows that even the usage of the simplest model of ANN such as Rosenblatt's perceptron could provide good results and compliance with rule-based FDD system. Mavromatidis, Acha, and Shah (2013) developed a diagnostic tool for a supermarket using the ANN models. This tool evaluates, on the basis of suitable explanatory variables, the energy consumption of each supermarket subsystem to provide the energy baseline, and then performs the fault detection analysis. Shang, Zhou, and Yuan (2014) introduced an automatic fault detection method for automobile transmission and a fault diagnosis expert system for newly assembled transmission. The order spectrum analysis method was used to analyze vibratory signals of the automobile transmission. After the initial feature vectors set were obtained and improved, genetic search strategy was used to select fault features, so as to reduce the dimension of the feature vector set. Selected feature vector sets were inputted into the neural network for fault identification and classification of the newly assembled automobile transmission. A large number of data was collected and analyzed from an industrial site and the proposed algorithm was verified to be effective and exact. Rossi, Velázquez, Monedero, and Biscarri (2014) proposed an effective modeling technique for determining baseline energy consumption of a CHP plant subjected to a retrofit. The study aimed to recreate the post-retrofit energy consumption and production of the system in case it would be operating in its past configuration (before retrofit). Two different modeling methodologies were applied to the CHP plant: thermodynamic modeling and artificial neural networks. A high level of robustness was observed for neural networks against uncertainty affecting measured values of variables used as input in the models. The study demonstrated the great potential of neural networks for assessing the baseline consumption in energy intensive industry and for overcoming the limited availability of on-shelf thermodynamic software for modeling all specific typologies of existing industrial processes.

The present work is devoted to the problem of fault detection using real building energy consumption data through simplified robust algorithms. In this study, different pattern recognition techniques are used to analyze 15 min timestamp recorded data of active electrical power for lighting and total active electrical power of eight adjacent buildings (hereafter referred as cluster of buildings). As demonstrated above few papers are focused on artificial intelligence and data mining techniques applied to the specific sector of building energy consumption fault detection.

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