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Activity-aware HVAC power demand forecasting

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ABSTRACT

The forecasting of the thermal power demand is essential to support the development of advanced strategies for the management of local resources on the consumer side, such as heating ventilation and air conditioning (HVAC) equipment in buildings. In this paper, a novel hybrid methodology is presented for the short-term load forecasting of HVAC thermal power demand in smart buildings based on a data-driven approach. The methodology implements an estimation of the building's activity in order to improve the dynamics responsiveness and context awareness of the demand prediction system, thus improving its accuracy by taking into account the usage pattern of the building. A dedicated activity prediction model supported by a recurrent neural network is built considering this specific indicator, which is then integrated with a power demand model built with an adaptive neuro-fuzzy inference system. Since the power demand is not directly available, an estimation method is proposed, which permits the indirect monitoring of the aggregated power consumption of the terminal units. The presented methodology is validated experimentally in terms of accuracy and performance using real data from a research building, showing that the accuracy of the power prediction can be improved when using a specialized modeling structure to estimate the building's activity.

1. Introduction

1.1. Background and motivation

Recent advances in the functionalities of modern Building Energy Management Systems (BEMS) in terms of monitoring and supervision [1,2] have paved the way in the framework of smart buildings for the introduction of Demand-Side Management (DSM) practices [3], which are one of the most important methods for achieving energy savings [4]. The increased insight derived from this progress has been instrumental in the further study of context-aware solutions that are capable of improving the energy efficiency of technical services in BEMS by building on the expanded knowledge available [5]. By accounting for up to 40% of the power consumed in buildings, heating ventilating and air conditioning (HVAC) systems, in particular, have attracted a substantial share of current research efforts [6,7].

In modern buildings, load modeling and forecasting methodologies able to predict the future power demand of HVAC systems are an important concern of installation managers due to the useful knowledge that they provide [8], since real-time demand information plays a role in mitigating energy waste [9]. Several types of methodologies exist, being data-driven approaches the most prevalent. However, when applied to HVAC systems, these methodologies are mostly aimed at forecasting the consumption load [10]. Instead, focusing on the thermal power demand may help abstract from performance differences caused by regulation systems and to better reflect the power needs of the facility. Automation systems can benefit from this information in order to make decisions autonomously by following energy-saving optimization strategies. This is especially true for the control of HVAC equipment, where the predicted load could be used for implementing model-predictive control strategies. Multiple control approaches applied to HVAC systems that could benefit from this information can be found in the literature, such as the planning of energy storage during off-peak periods using cooling storage systems [11]. Others also include the planning of adequate startup and shutdown times for heating and cooling equipment in order to save energy by meeting the right amount of power demands, and for the orchestration of machine actuations in installations where multiple machines are available [12]. Furthermore, the combination of HVAC

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Nomenclature

ABM	Agent-Based Modeling
AHU	Air Handling Unit
ANFIS	Adaptive Neuro-Fuzzy Inference System
BEMS	Building Energy Management System
DSM	Demand-Side Management
HMM	Hidden Markov Model
HVAC	Heating Ventilating and Air Conditioning
MAE	Mean Average Error
MAPE	Mean Absolute Percentage Error
MAX	Maximum Error
OPC	Open Platform Communications
R^2	Coefficient of Determination
RMSE	Root Mean Squared Error
RNN	Recurrent Neural Network
SCADA	Supervisory Control and Data Acquisition

load forecasting with machinery efficiency maps represents an underexploited avenue of improvement with a high potential for the optimization of the operation of the system. That is, the demand anticipation and the utilization of the most suitable machine for each situation would provide a positive affectation to the overall equipment's performance, which is a significant present-day problem in building management and maintenance. Indeed, the overall efficiency of the installation could be improved, since the current most common method for allocation HVAC capacity is based on setting the same water temperature thresholds on all the available machines [13].

Even though this framework represents one of the main current research interests stated by the related scientific community, the obstacles to its implementation are double-sided. First, the efficiency maps are difficult to obtain when precision beyond the manufacturer's sparse figures is desired, as they would require extensive testing of the unit in each installation, and would likely drift over time as the equipment deteriorates with aging. Secondly, the methodologies for obtaining load predictions in HVAC systems are not mature enough and their implementation can be quite challenging due to the potential complexity of energy systems [14].

1.2. Literature review

In the recent literature, considerable scientific effort has been committed to the research of load forecasting algorithms and methodologies, as seen in the latest review papers [15]. A comprehensive review of more than one hundred papers on electrical load forecasting defined a general taxonomy for selecting modeling algorithms from the point of view of their popularity in different applications, indicating that data-driven approaches are mainly used in short-term forecasting applications due to their complex dynamics [16]. In contrast, a comparative analysis studied eleven modeling algorithms from the point of view of their performance when applied to the same dataset, revealing their applicability in different scenarios including cases with limited data or high variability [17]. However, even though numerous general-purpose approaches exist for the implementation of load forecasting, their limitations are revealed when applied to real HVAC systems, which are mainly related to the difficulty of adapting the predictions to the power demand changes caused by fluctuations of influencing parameters, such as the weather and the occupant's behavior during the day [8].

In this regard, recent studies as the one presented by Peña et al. in [18], confirm the significant correlation between the occupancy of the building's spaces and the HVAC equipment's actuations and consequent operational regime changes. This, as promoted by different authors, as Hong et al. in [19], indicates that the occupancy should be a key aspect in the research of energy usage in buildings, because of its potential contributions to efficiency improvements. Actually, a recent review of energy efficient ventilation strategies concluded that large amounts of energy are being wasted because of conditioning building areas that have effectively empty periods of time, and that accounting for these may help to greatly increase efficiency [20]. Indeed, most of the current load simulation and forecasting methodologies show a lack of occupancy awareness, while the available studies dealing with the integration of occupancy data into load forecasting systems to enhance the accuracy of power demand predictions present critical limitations and insufficient proficiency [21].

Similarly, a recent review of artificial intelligence methods for load forecasting in buildings suggested that the integration of occupancy data has the potential for improving energy predictions [22]. Moreover, it was stated by Massana et al. in a study of the application of neural networks for building energy forecasting, that occupancy-based inputs should be taken into consideration in future studies because of the impact that the occupancy can have on the building's thermal energy usage. This is shown in [23] and further developed in [24], where several attributes were studied, concluding that it would be useful to create occupancy indicators for improving the prediction capabilities.

On this subject, some methodologies for the modeling and forecasting of occupancy in buildings exist, being Agent-Based Modeling (ABM), and Hidden Markov Models (HHMs) the most common. ABM approaches try to mimic the behavior of occupants of a building in order to simulate either occupancy patterns or their effects at the occupant level [25], hence being too fine-grained for full building applications. Alternately, HMMs are stochastic processes that naturally fit the problem of modeling occupancy patterns, because they treat occupancy as a series of transitions between states and attempt to estimate and simulate the probabilities of transitions among such states [26]. HMMs are useful at low aggregation levels, for example for assessing the probability of a given space becoming occupied, but are not a good fit for big scenarios, as the complexity grows exponentially with the number of zones [27]. Another disadvantage of HMMs at high aggregation levels is that their future state is a function of their current state, not taking into consideration past states. This property could neglect important features of the aggregated occupancy, such as the ratio of change. Indeed, complete and viable solutions are yet to be investigated, and the proper way to monitor the occupancy, to define the indicators and to integrate them into a load forecasting system remains to be established.

1.3. Innovative contribution

In this paper, an HVAC thermal power demand forecasting methodology composed by the integration of a power demand model and an activity indicator model is studied. The methodology aims to extract the occupancy patterns in order to determine the level of activity in the building and thus to improve the accuracy of the power demand forecasting. With this objective, the building's historical database is divided into occupancy and load data for separate preprocessing. Then, an activity indicator is built and a model is implemented using Recurrent Neural Networks (RNN) to enhance the consideration of dynamic temporal patterns, while the power demand characterization is carried out by means of a state-of-the-art Adaptive Neuro-Fuzzy Inference System (ANFIS) structure. Finally, a reliable and robust power demand forecasting model is obtained by the serialized fusion of both inference systems.