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Building-level power demand forecasting framework using building specific inputs: Development and applications

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HIGHLIGHTS

- ARX models and physics based modeling approaches for power forecasting.
- Compare sensitivity of input/output relationships and relevance to decision making.
- Use of controller metrics as ARX model inputs helps capture precooling behavior.
- Forecasting ability demonstrated on simplified building model and real data.

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ABSTRACT

In this paper, the development of a general framework for building level power demand forecasting and its applications to supervisory control and demand management are presented. Models of thermal loads, while rigorous and insightful, do not directly extrapolate to measures of power consumption and cannot be easily applied to a variety of buildings. Ultimately, building operators are interested in managing power consumption as energy costs and opportunities are directly related to the power variable. Our work develops Auto-Regressive models with eXogeneous inputs (ARX) to forecast power demand in conjunction with existing physics based modeling approaches and enhances the current control framework for building energy management. The main contributions of this work are identifying and incorporating building level measurements as inputs, and evaluating the use of power forecast models for supervisory control and demand response (DR). The move towards a smarter grid is expected to provide extensive data on building conditions and power consumption, which we can include in the model development. Options for model inputs and outputs are investigated depending on possible measurements, and their effect (or sensitivity) on the modeling and decision making processes are evaluated. It is shown that an appropriate selection of exogenous inputs related to the control action is necessary to capture the effect of common demand management practices such as precooling. The forecasting capabilities are also demonstrated on a simplified building model and on data collected from a real building.

1. Introduction

This paper describes an approach to model power consumption of individual buildings utilizing local (building specific) variables. The motivation to develop this model is the lack of advanced control approaches based on power consumption, and to provide for easy adoption of demand response (DR) programs. Our approach is applicable to a wide variety of buildings but the specific focus of this paper is commercial buildings, which consume over one third of the electricity generated in the United States and are projected to account for 40% of the increase in electricity demand by the buildings sector over the next 25 years [1]. Most of the prior literature has focused on residential buildings [2,3] and only specific types of commercial buildings such as multi-zone offices [4,5]. Generic and practically applicable solutions for commercial buildings are more challenging because of wide variations in the type, size and usage of commercial buildings.

In the near future, it will be possible to equip buildings with extensive sensing technology in the indoor environment and advanced meters for power consumption [6]. These improvements in monitoring are driven by the push for a smart grid and more communication between electricity consumers and the utility companies [7]. The presence of these devices provides a significant

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amount of data that can be exploited in a sophisticated building energy management system. Thus, as part of developing a model to forecast power consumption, our work investigates the use of these measurements and their importance in improving the quality of the model.

The research on building energy management has heavily focused on the modeling and advanced control of building Heating, Ventilation and Air-Conditioning (HVAC) systems. The past work is particularly focused on developing models of building thermodynamics for use in sophisticated controllers such as Model Predictive Control (MPC) [8]. These control approaches require extensive modeling effort for each building. The energy management is then based on decisions regarding thermal energy storage using insight from the model and an understanding of the occupant comfort requirements [9]. As a result, while the research on this topic is rigorous and extensive it cannot be easily applied to the wide variety of commercial buildings (which range from office space to malls to telecom base stations). Also, Existing HVAC energy management solutions do not directly consider power as a decision variable – even though costs are directly a function of power usage. Knowledge of the power demand is also desirable when making decisions regarding demand management (DM – refers to local energy management) because it affects the ability of the building(s) to participate in demand response (DR) services. Power modeling and the effect of DM decisions are also of interest to the utility. Thus there is motivation for modeling, in addition to thermal loads, building-level power use in a manner that can be easily replicated and repeated for a variety of buildings under a given DR scenario. Our method achieves this by integrating data-driven modeling techniques into controllers based on existing physics based modeling approaches.

To summarize, this paper describes a general power modeling framework to forecast HVAC power demand in an individual building utilizing building-specific measurements, and discusses the applicability of this model for purposes of system control and DR. A preliminary version of this work on the applicability of ARX models for power demand forecasts was presented at [10]. We consider a time series based Auto Regressive eXogenous (ARX) modeling approach. However there are many variations, like ARIMAX and other data driven models or the use of Kalman Filter for online parameter estimation [11–15], which can be implemented for improved modeling accuracy. Rather than focus on the model quality, this work has a broader scope. The purpose of this work and the consequent contributions are (i) to study the use of models for forecasting future power demand with or without thermal RC models and other models that describe the building physics, (ii) investigating the options for model inputs and outputs depending on possible measurements and establishing their effect (or sensitivity) on the modeling and decision making processes, and (iii) demonstrating general approaches and strategies to utilize the forecasted power demand in analyzing DR capabilities in commercial buildings and for control and optimization purposes. The features related to model development and usage are demonstrated by two case studies – one based on simulated data and another based on data collected from instrumented real-world buildings – that demonstrate the generic nature and practical value of our approach.

The remainder of this paper is structured as follows. In Section 2, a discussion on commercial building demands and the place of power modeling and forecasting in a supervisory control framework is presented. Section 3 presents the process of ARX modeling to forecast power demand by discussing model inputs, their sensitivity to the output and the focus on subsystem level power modeling. Finally, in Sections 4 and 5, two case studies are presented to demonstrate the modeling process and its usage for different applications such as DR.

2. Building power modeling and control

This section describes several aspects of the power demands or loads in a commercial building, their modeling and control and provides the background for the following sections. We describe different types of building demands and explain our focus on modeling HVAC demands, though our approach is flexible enough to be easily adapted to other demands as well. We explain the conceptual place of a power modeling framework, such as ours, in building supervisory control. Finally, a short discussion on building level load forecasting is presented to motivate the development of our ARX based power modeling approach in the next section.

2.1. Commercial building demand types

Commercial buildings are defined as any structure not used for residential or agricultural purposes [16]. Electricity in commercial buildings is used mainly for space heating and space cooling, ventilation, lighting, cooking, water heating, refrigeration, office equipment and computers [16]. Electric Vehicle (EV) charging can constitute a significant demand in the future [2]. The motivation for nearly all research on modeling and controlling these loads is centered on reducing both overall and peak energy consumption. It is important to note that a single demand type may be satisfied through the use of different physical systems when comparing individual buildings (e.g., space cooling met by window air conditioners or a centralized chiller system). In our approach we avoid relying on domain specific knowledge when modeling a system's power demand. This is a major contribution of our approach and it provides the flexibility to extend the modeling approach to other loads and various building types.

In this paper, we adhere to this trend and focus on shifting cooling loads. However, we postulate that many of the core concepts in our modeling approach can be easily adapted to other systems and DR techniques depending on the types of measurements available. From this broader perspective we address the question of whether or not a model can be used to predict the benefits of specific DR actions by focusing on whether or not the model is able to capture such behavior.

Irrespective of the type of demand, a control framework has to be formulated at the local (building) level in order to utilize the demand devices for energy management or DR. In the next subsection, the usage of a power model and the existing supervisory control framework are discussed.

2.2. Supervisory control of building loads

A supervisory controller is usually tasked with determining optimal system states and controller setpoints based on external conditions such as electricity price. The general framework for such an approach is shown in Fig. 1. This framework can be tailored to many of the types of demands described in 2.1 but we keep the discussion specific to HVAC systems.

In an advanced building energy management system the supervisory control is commonly implemented using Model Predictive Control (MPC) [17]. In MPC, an optimization is used to determine the optimal indoor temperature setpoints needed to shift cooling loads to off-peak times without sacrificing occupant comfort [8]. Because the model is a crucial component of a supervisory controller's calculations, there is substantial literature on data-driven and physics based models of buildings [18]. Although they are not the focus of our work, they will play a role in our proposed forecasting process and are therefore reviewed briefly in Section 3.

Resistance capacitance (RC) thermal network models have been given much attention by the building community. Examples of RC