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Energy disaggregation analysis of a supermarket chain using a facility-model

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ABSTRACT

Supermarkets are energy intensive. To optimize their energy consumption, major subcomponents need to be identified through disaggregation. Disaggregation can be challenging in supermarkets due to lack of instrumentation at sufficient resolution, especially in developing economies. Also, the diversity in the space cooling systems across stores adds to the complexity. This paper presents a novel approach to disaggregate store level energy into weather-dependent and weather-independent components using facility energy models. The novelty lies in the fact that the approach does not require sensory minutiae or extensive sub-metering. The approach identifies the key drivers of a supermarket's energy consumption, and also estimates gaps in the performance with possible root causes. A case study on using the proposed approach to analyze 94 stores from a supermarket chain is presented. Key findings include: (i) weather-independent loads can dominate weather-dependent loads. (ii) Refrigeration cases contribute to space cooling too. Cooling requirement of these cases can be more than that of space cooling. (iii) For these reasons, occupancy may not appreciably influence a store's energy consumption. (iv) In the supermarket chain studied, various reasons for poor performance spanning both design and operations were discovered, viz., higher deadloads, oversized HVAC systems, and additional load turn-on hours.

1. Introduction

Supermarkets are among the most energy intensive classes of buildings. In the USA, the average annual energy intensity for grocery stores is 552.2 kWh/m^2 [1]. The energy consumed by a supermarket is more than twice the energy consumed by a hotel or an office of the same size [2]. The energy consumption also affects the profit margins of supermarkets, which are already low around 1–2% [3]. It has been estimated by US Energy Star that $1 reduction in energy cost is equivalent to increasing sales by $59 [4]. The electrical energy consumption can vary widely from an annual intensity of 700 kWh/m^2 of sales area to over 2000 kWh/m^2 in convenience stores [5]. Therefore, from both sustainability and economic perspectives, it is critical to analyze, understand, and reduce the energy consumption of supermarkets. Despite their importance, energy consumption of supermarkets has been less studied in research literature.

Supermarkets typically operate as a chain, i.e., they have tens to hundreds of stores distributed across various locations. It is laborious and expensive to undertake a detailed manual energy audit of each of the individual stores to reduce their energy consumption. Therefore, it is important to analyze consumption across stores systematically and identify stores with a higher potential for energy savings. Subsequent manual energy audits can focus on those short-listed stores alone.

This overarching goal of identifying stores from an ensemble with good potential for energy savings can be posed as a series of inter-dependent questions:

- Is it possible to estimate the contribution of dominant load categories within a store by disaggregating a store's overall energy consumption?
- How close are the estimated consumption of various load categories to their design conditions? Answering this question will allow us to rank stores based on the difference between estimated

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dominant loads and their design values. We can consequently focus on low-ranked stores.
- Are there any patterns in the estimated performance gap among the stores? This would help identify possible root causes of the performance gaps.

A key challenge in answering the above questions is limited data availability, particularly at the temporal or spatial (i.e., sub-system) resolutions needed for detailed analysis. This is due to several reasons:

- *Lack of sub-metering*: Individual stores may not have sub-meters installed to measure the consumption of individual sub-systems/equipment. This is true especially in brownfield facilities of developing economies. Store managers require a business case to install sub-meters owing to the capital costs involved. Ironically, a business case typically cannot be made unless the questions are answered.
- *Lack of sensors*: It is possible that certain data, such as age related performance deterioration, may not be available due to absence of appropriate instrumentation (e.g., BTU meters, air flow meters, etc.). Such instrumentation, again, requires a business case.
- *Scale of the exercise*: If a large number of facilities are involved in the energy analysis exercise, the effort required to collect/estimate relevant parameters and details of individual loads across all the facilities becomes unmanageable. Further, climatic conditions change across stores, adding to the complexity.

Several approaches have already been proposed in the literature for estimating the energy performance gap of a building either with respect to standard or relative reference figures [4,6,7] or design conditions [8–12]. A detailed analysis of related work is at the end of this section. However, these approaches either do not give enough insights into the possible causes for poor performance or require too many inputs to be useful when analyzing a large number of buildings.

We present a method to systematically answer these questions by using facility energy models (in EnergyPlus [13]) to partially overcome the gaps in data availability. Fundamentally, the energy consumed by a building, E has two components: *weather-independent* (E_{wx}) and *weather-dependent* (E_w). The weather-independent component is insensitive to weather conditions and typically includes lights, computers, security systems, and check-out tills. The weather-dependent component is sensitive to the ambient weather conditions and typically includes HVAC and refrigeration systems. Our method disaggregates the overall energy consumption of a supermarket store (buildings, in general) into weather-dependent and weather-independent components. As we will see in later sections, even such coarse-grained disaggregation can provide interesting insights on the energy consumption behavior of an ensemble of stores.

We also present **a case-study involving** 94 **stores from a real world supermarket chain in an emerging economy**[1]. In previous work [14], we had undertaken a data-driven study of the meter logs of these stores. However, the lack of submetering made it difficult to reason about the overall consumption for an in-depth analysis. In this work, we adopt a fundamentally different model-driven approach to not only **identify** the good/bad stores but also discover the possible **causes for poor performance**. Specifically, our **contributions** in this paper are as follows:

- We propose a methodology to disaggregate the total energy consumption of a building into weather-dependent and weather-independent categories using limited, readily obtainable data.
- We use the disaggregation methodology in the context of a supermarket chain and analyze various drivers. For instance, we explain why ambient temperature influences the energy consumption of a store but occupancy does not.
- We use the disaggregation methodology to identify stores with poor energy performance and possible causes (both design and operational) for the poor performance.

The proposed disaggregation based analysis is generic and can be utilized for several other building types such as retail outlets, hospitals, restaurants, and hotels.

Work related to this paper can be broadly categorized as follows.

1.1. Non-intrusive load monitoring (NILM)

NILM techniques that breakdown the overall energy consumption signal into constituent loads have been in vogue since the 1990s. Hart [15] proposed a technique based on combinatorial optimization and edge detection to disaggregate loads. Over the past decade, techniques based on feature detection, clustering and other methods have been proposed [16–19]. Several NILM datasets [20–22] and even tool kits [23] have been made available for researchers.

These works predominantly focused on residential settings [24,25,17] where the number of equipment is significantly smaller than found in commercial buildings. These methods are impractical to use in commercial buildings, due to equipment heterogeneity in large facilities, and lack of sufficient (vast) data. These works also require the aggregate consumption signal at finer resolutions (1 s or less) along with detailed signature of individual appliances. Our approach differs from them in that we work with coarser granularity aggregate consumption signal (at 1 h intervals). Further, we focus on large commercial facilities and breakdown the aggregate consumption signal into coarser load categories rather than into individual loads.

Energy disaggregation in large facilities has also been studied in some works. Ref. [26] proposes disaggregation of electricity load in an university campus when large amount of data is available. Clustering based algorithms were proposed for processing large quantities of data for load disaggregation. In [27], the total energy in a large facility is split into HVAC and non-HVAC consumptions, in which benchmark EUI (energy usage intensity) obtained from similar building stock is used to estimate the latter. The HVAC consumption is obtained by subtracting the non-HVAC benchmark EUI from the aggregate energy, which is in turn compared with cooling load estimated from heat balance principles. Our approach is similar to [27] in terms of the disaggregated load categories, however more rigorous, for estimating the non-HVAC consumption, as opposed to using average benchmark EUI values. Besides, our approach does not require the HVAC field measurements and other data minutiae, as used in [27,26].

Ref. [28] proposes a disaggregation methodology to obtain end-usage breakups in banks. Data from 1890 bank branches is used to obtain a simple linear regression for benchmarking the aggregate consumption, and using climate specific building simulation, the aggregate is split into different end-uses. This work shows that regression approach is not sufficient, and building specific data are necessary to make corrections for the local effects. This work uses 41 building variables along with others, to obtain the end-usage (lighting, ATM, electric equipment, cooling fans) estimations through building simulations. Other works based on data intensive techniques for load identification include [29,30]. In our work, we will show that aggregate energy can be decomposed

[1] The identity of the chain is withheld due to confidentiality requirements.