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Analyzing heating equipment's operations based on measured data

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ABSTRACT

A heating (or cooling) equipment's operation is consisted of cycles. In each cycle, the equipment operates to generate heat to raise the room temperature and shuts down when the desired temperature is reached. This research studies the cyclic characteristics of typical gas burning furnaces. Each cycle is divided into runtime and idle states. The runtime process is further decomposed into three phases: startup, stable operation and shutdown. The measured data shows that the length of runtime in each cycle remains constant but idle time varies from cycle to cycle responding to outdoor environmental conditions. Four Data Mining Algorithms (DMAs) including k-Nearest Neighbors (KNN), Naive Bayes (NB), Support Vector Machines (SVM) and Artificial Neural Networks (ANN) are used to analyze the relationship between cycle idle time and weather conditions based on actual minute-by-minute electricity usage data of two furnaces in a residential house and weather data from the near-by weather station for a period of four months (January to April 2011). The obtained results show that SVM and ANN provide more accurate predictions of idle time. Parametric correlation analysis indicates that indoor–outdoor temperature difference and wind speed are two key parameters affecting cycle idle time. The obtained results on the cyclic characteristics of a heating equipment provide essential information for estimate heating energy demand according to weather conditions, determining the equipment's energy efficiency, and diagnosing potential faults in its operation.

1. Introduction

Buildings consume 40% of U.S. primary energy, including 72% of electricity and 36% of natural gas [1,2]. They contribute 40% of U.S. carbon emissions [3]. The building sector is the largest energy consumer, ahead of industry (32%) and transportation (28%) [2]. It had driven 87% of the growth for new power plants between 1985 and 2006 [1]. Improving energy efficiency has been recognized as one of the most cost-effective means to reduce energy consumption and gas emissions. It is widely referred as the "low-hanging fruit" for many perceived benefits – lower energy bills, improved air quality, reduced greenhouse gases, increased energy security, and a deferred need to invest in new infrastructure [4,5]. Research has shown that buildings can achieve 50–60% savings at moderate costs [4–6]. Energy efficiency provides a national sustainable energy pathway [4]. However, numerous studies documented that economically attractive and energy-saving opportunities have yet to be widely adopted [6,7].

The Nation's building stock consists of 128 million residential units and 4.9 million commercial buildings. Residential and commercial buildings account for 22% and 18% respectively of the total 40% energy consumption [8,9]. Large commercial buildings are typically installed with advanced monitoring and control devices, and are managed by professional building engineers [10]. On the other hand, owners of residential and small commercial buildings have neither financial resources nor technical expertise to analyze and manage their energy consumption [11,12]. Homes around the world currently have no means to judge their energy use other than monthly utility bill [13]. A monthly bill does not provide much information other than to inform the homeowner of his/her monthly consumption, payment and payment deadline. Recent advancement in the market is mainly dominated by metering and display technologies [14,15]. A smart meter can provide a homeowner with 15-min-interval readings on electricity use instead of monthly bills. Instantaneous feedback devices can convert electricity consumption in dollar amount so that that the homeowner can be actively involved in monitoring and controlling his/her electricity use. Studies show that direct instantaneous feedback on

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Nomenclature

AC	air conditioning
ANN	Artificial Neural Networks
CT	cycle time
DMAs	Data Mining Algorithms
HVAC	heating, ventilation and air conditioning
IT	idle time
KNN	k-Nearest Neighbors
MAE	mean absolute error
MPE	mean prediction error
MSE	mean square error
NB	Naive Bayes
OT	operating time
SVM	Support Vector Machines
SU	startup time
SO	stable operation time
SD	shutdown time
TD	temperature difference

household electrical demand can reduce energy consumption by 10–15% [12,16]. However, studies also show that early savings tend to diminish after the curios period is over and the homeowner is less interested and less involved [16,17].

Reducing wasteful and low-priority spending is an effective way to improve an individual's finance. Similarly, reducing energy wastes and low-efficiency use is a viable approach to improve energy efficiency in buildings. Like money, energy should be used where it is needed and be used efficiently. Imaging that a credit card company would only provide the cardholder with a total balance at the end of each billing period, how could a financial advisor use that information to help the consumer improve his finance? Many homeowners are frustrated with the reality that they do not see their monthly electricity bills come down after thousands of dollars were invested in energy efficiency measures, such as high efficiency AC or low-e windows. Such sentiment makes it extremely difficult to convince them to invest in other energy efficiency measurements. Detailed usage data of specific end loads provides essential information for efficiency evaluation, as the life principle states, "you cannot manage what you don't measure" [18].

Energy consumption in a building at any point in time is the sum of various end uses. Each end use is linked to the operation of an appliance/device (e.g. refrigerator), lighting at a particular location (e.g. in the living room) or equipment (heating, ventilation and air conditioning – HVAC). A device's operation can be characterized by a series of operating cycles, each of which is marked a paired on-off pattern.

The cyclic data shows the utilization, energy intensity, and the amount of energy used by the device so as to determine its energy efficiency level and improvement potential. For instance, a 60 watts incandescent light bulb consumes 60 watts of electricity in an hour, an equivalent compact fluorescent (CFL) bulb uses about 15 watts, and a similar light emitting diode (LED) bulb consumes 8 watts only. A changing trend of the energy intensity and operating patterns may indicate the device's performance degradation over time, a sign for diagnosing its working conditions. The length of a device's runtime may expose the device's faulty conditions and incurred energy waste. A faulty device may consume extra energy or not be able to provide its intended function. For instance, if the AC unit operated a long time to cool the house in each operating cycle, this would indicate a low efficiency or even faulty AC unit.

A furnace's function is to supply hot air to maintain the conditioned space at the desired temperature. It turns on when hot air is needed and shuts down when the desired temperature is reached. A complete cycle is defined by two consecutive turn-on events of the equipment as shown in Fig. 1. Each operating cycle is consisted of two states: operating and idle. The operating phase can be divided into three stages: startup, stable operation and shutdown. The equipment is off when it is in idle.

This research is to evaluate the operating patterns of the furnaces in a residential building. It covers the following issues: (1) data collection and processing of the electricity consumption data and weather data at the site; (2) statistical analysis of the characteristics of the operating patterns of furnaces; (3) predicting cycle idle time of furnaces using four DMAs: k-Nearest Neighbors (KNN), Naive Bayes (NB), Support Vector Machines (SVM) and Artificial Neural Networks (ANN).

2. Data collection and processing

An occupied house was used in this study. The house was built in 2005 and is located in Omaha, Nebraska. The 2-story house has a total floor area of 421.41 m^2. Two gas furnaces are installed. Furnace 1 (Lennox G40UH-488-090, input = 92,845 kJ, output = 64,991 kJ) provides heat to the basement and the first floor. Furnace 2 (Lennox G40UH-36A-070, input = 69,634 kJ, output = 48,744 kJ) supplies heat to the second floor.

The weather data was obtained from a nearby weather station which records local weather conditions in 20-min intervals. The distance between the station and the object house is 3.5 km, as shown in Fig. 2.

2.1. Data collection

An E-Monitor system by Power House Dynamics [18] was installed to monitor the minute-by-minute electricity consumptions of the 24 circuits at the main switchboard of the house. Each record shows the electricity consumptions of the 24 channels in a minute of a given calendar day (month/day/year:hour:minute).

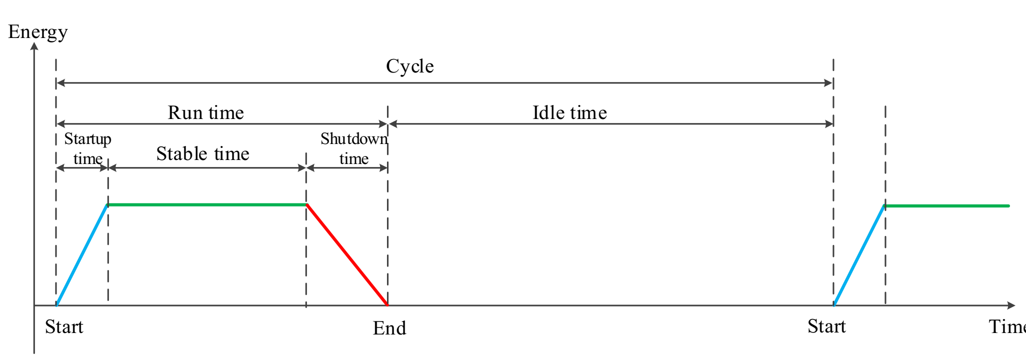

Fig. 1. Operating cycles of a furnace.