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Monitoring and autonomous control of Beijing Subway HVAC system for energy sustainability

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ABSTRACT

As the backbone of urban public transportation, subways are also major consumers of energy. More than 30% of the total energy is used to operate the heating, ventilating and air conditioning (HVAC) subsystems. If it were possible to reduce energy consumption of HVAC subsystems a few percent, a significant quantity of electricity would be saved. From 2012 to 2013, we conducted field studies and developed autonomous control system for saving energy of HVAC systems in Beijing subway stations. The energy consumption features and the load signatures of the HVAC systems were investigated and we deployed comprehensive environment monitoring, passenger flow monitoring and run-time data logging subsystems to monitor and investigate the above features in several metro stations. The extracted features showed a broad space for optimizing current HVAC systems' operation to save energy. Based on the insights learned from the field studies, we spent four months to develop and deploy autonomous HVAC control systems in three metro stations. Up to now, the developed autonomous control systems have worked well and the energy logs showed that the autonomous control system helped the metro stations reduce energy in a range from 20% to 38% than the conventional control strategy. We introduce key insights learned for energy saving and some future research directions.

Introduction

Beijing Subway is a backbone transportation network that serves the urban and suburban districts of Beijing municipality. It has 17 lines, 227 stations and 456 km of track in operation (Anon., 2013), operated by two companies, Beijing MTR (operates 14 lines) and Hong Kong MTR (operates 3 lines). It now ranks third in length in the world after Seoul and Shanghai, and serves more than 7.5 million passengers a day, which is the busiest in China. It served totally more than 2.46 billion passengers in 2012 .

Because of its large scale and heavy load, Beijing subway consumes a great amount of energy everyday. A survey on the daily energy consumption of Beijing subway was conducted in Lu et al. (2011), in which, a steep, i.e., more than 30% increment of energy consumption was found in July than that in April. It indicates the heavy energy consumption by the air conditioning subsystems for cooling and ventilation in the summer season.

In 2012, we took a more detailed study to Beijing Subway to examine the electricity consumption in a finer granularity. We disaggregated the overall consumption into the consumption of train propulsion subsystem, lighting subsystem, air conditioning subsystem and other subsystems. The investigation was conducted in line A operated by Hong Kong MTR. For the sake of information privacy, the names of the line and the names of the stations are set anonymous in this paper. Our investigation showed that the energy consumption of air conditioning subsystems ranged from 31% to 40% in different subway stations. The overall electricity consumption of air conditioning subsystem in the whole line was more than 18,190,000 kWh per month. Therefore, if the energy consumption of the HVAC system can be reduced a few percents, impressive quantity of electricity would be saved.

For this goal, we investigate the energy consumption signatures of the HVAC system by deploying environment monitoring sensors and smart meters. The passenger flow was recorded by the ticket checking systems. By collecting and processing these data, the run-time features, load and supply signatures of the HVAC subsystems were investigated. It showed that: there were some operating problems in current air conditioning systems in subways as follows: 1) the mismatching of loads and supplies; 2) control is not well adaptive to the variation of environments and passenger flows;

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3) improper control regarding the pumps and valves, etc. To address these problems, we developed an autonomous control system for energy efficiency of HVAC systems.

From April 2013 to July 2013, we spent four months to design, construct and deploy the autonomous HVAC control systems for the three metro stations based on the insight learned from the eld studies. The design emphasized adaptivity of the HVAC system to match its cooling supply to the variation of the heating loads. For practical considerations of system reliability, we designed rule-based adaptive control strategies and implemented these strategies by control cabinets, frequency adapters, and automatic valves. The systems have worked well through the summer season of 2013. Up to now, by the energy logs collected in the last summer, the results showed that the autonomous control system not only provided satisfactory indoor temperature and humidity, but also reduced the energy consumptions of the three stations in the range from 20% to 38%. Some further research directions and insights learned from current deployments are discussed.

The remaining sections are organized as the following. Related works are introduced in Related Work section. Field studies and investigation to the features of subway HVAC systems are presented in Field Study and Insights for Energy Saving section. Load signature investigation is presented in Investigate the Load Signatures of HVAC section. Development and deployment of autonomous HVAC systems are presented in Autonomous HVAC Control System section. The energy saving performances are introduced in Energy Saving Performance section. The paper is concluded with discussions in Conclusion section.

Related work

The studying of smart and sustainable commercial and residential buildings has attracted great research attentions in the last two decades (Kelman et al., 2011; Tashtoush et al., 2005; Fong et al., 2006; House and Smith, 1995), because building consumes nearly 48% of total energy, as reported in the US (Al-Sallal, 2014). Many countries have presented different schemes to resolve building energy efficiency problem for balancing the economy growth and environment sustainability. Lamberts (1996) reported the sustainable building development in Brazil. Fulkerson et al. (2005) reported the situations and visions in OPEC countries. Weidou and Johansson (2001) reported the recent development of sustainable buildings in China. Among these approaches, sensing the real demand and optimizing the heating and ventilation supply to users by autonomous control is a common approach (Yang and Wang, 2012; Murayama et al., 2012; Gungor et al., 2010). The autonomous control policy adjusts the operation of the air conditioning, lighting, ventilation systems, etc. by onsite measuring the thermal condition, so as to reduce the energy consumption cost while maintaining satisfied indoor thermal comfort indexes (Wang and Ma, 2008). However, only limited results were reported about autonomous control for energy sustainability in subway HVAC systems.

The HVAC system in the subway differs from the HVAC systems of buildings because of the different structure of the building for heat exchanging and the different composition of the thermal demands in subway (Casals et al., 2014). A HVAC system in a subway station contains a set of subsystems, which can be divided into the gas-side and the water-side subsystems. When the subway is running, the system state changes much more quickly than that of the residual buildings. The heterogeneity, the complexity of these subsystems, and the high dynamics of the system states make the optimal control difficult. One of the difficulties is the lack of an exact model to describe the internal relationships among the different components. In the existing studies, a dynamic model of HVAC system for control analysis was presented in Tashtoush et al. (2005). The authors proposed to use Ziegler-Nichols rule, which is a heuristic method to tune the PID controller. A meta-heuristic simulation–EP (evolutionary programming) coupling approach was developed in Fong et al. (2006), which proposed evolutionary programming to handle the discrete, non-linear and highly constrained optimization problems. Multi-agent-based simulation models were studied in Andrews et al. (2011) to investigate the performance of HVAC system when occupants are participating. In Marzouk and Abdelaty (2014), thermal comfort in subways was monitored by using building information modeling method. In Yang and Wang (2012), swarm intelligence was utilized to determine the control policy of each equipment in the HVAC system. In Teeter and Chow (1998) neural network was used to identify the thermal dynamics in HVAC system. In Palensky and Dietrich (2011) an overview of demand side management was presented to summarize control methods used to response smart loads. But to the best of our knowledge, a thorough investigation to the subway HVAC system is still lacked. In this paper, we presented detailed field studies, environment monitoring and energy log processing to investigate the load signatures in subway HVAC systems and developed autonomous control systems accordingly.

One of the most closely related work is the SEAM4US (Sustainable Energy mAnageMent for Underground Stations) project, which was established in 2011 in Europe (Anon., 2011). It studied the metro station energy saving problem from the modeling and controlling aspect. Multi-agent models were proposed for the complex interactions of energy consumption in the underground subways (Serban et al., 2012). Researchers in the project have also proposed adaptive and predictive control schemes for controlling ventilation subsystems to save energy (Giretti et al., 2012). This project is theoretical and not implemented.

Another related work reported the factors affecting the range of heat transfer in subways (Hu et al., 2008). The authors showed by numerical analysis how the heat was transferred in tunnels and stations. Reference Awad (2002) studied the environmental signatures in the subway metro stations in Cairo, Egypt, which showed the different environment characteristics in the tunnel and on the surface.

Comparing to these existing work, we presented not only a comprehensive field study of the subway HVAC energy consumption situation and load signatures, but also an autonomous control systems and running results in several metro stations.

Field study and insights for energy saving

At first, field study results and the insights learned for energy saving will be presented. In 2013, we collected the electricity billing logs and the logs of AC meters from line A of Beijing subway to investigate the energy consumption characteristics of the subway HVAC.

Disaggregation of annual energy consumption

A disaggregation approach was conducted to investigate where the energy has gone in the subway. In particular, the overall energy consumption was divided into the consumption of 1) the propulsion system, 2) HVAC, 3) Lighting, and 4) others. Because the line under investigation is a new line, it provides detailed energy logs of each subsystem. Even the detailed consumption of the lights in each region are available. By processing these energy consumption logs, the disaggregated energy consumption of 14 stations in the line are shown in Fig. 2.

The portion taken by the HVAC system ranges from 31% to 40% in different stations. Note that this is the portion over a year. The HVAC systems work only for 4 months per year in Beijing, from June to September. So that the energy consumption of the HVAC systems per day in the summer season is striking. To further understand the