Energy for Sustainable Development 39 (2017) 1–12

Contents lists available at ScienceDirect

Energy for Sustainable Development

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

Yongcai Wang[a,*], Haoran Feng[b], Xiangyu Xi[b]

[a] Department of Computer Sciences, Renmin University of China, Beijing 100872, PR China
[b] Peking University, Beijing 100871, PR China

ARTICLE INFO

Article history:
Received 15 July 2014
Received in revised form 12 December 2016
Accepted 12 December 2016
Available online xxxx

Keywords:
Autonomous control
Air conditioning
HVAC
Energy efficiency
Sustainability
Subway

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;

* Corresponding author.
E-mail addresses: ycw@ruc.edu.cn (Y. Wang), haoran@pku.edu.cn (H. Feng), xixy@pku.edu.cn (X. Xi).

http://dx.doi.org/10.1016/j.esd.2016.12.004
0973-0826/

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

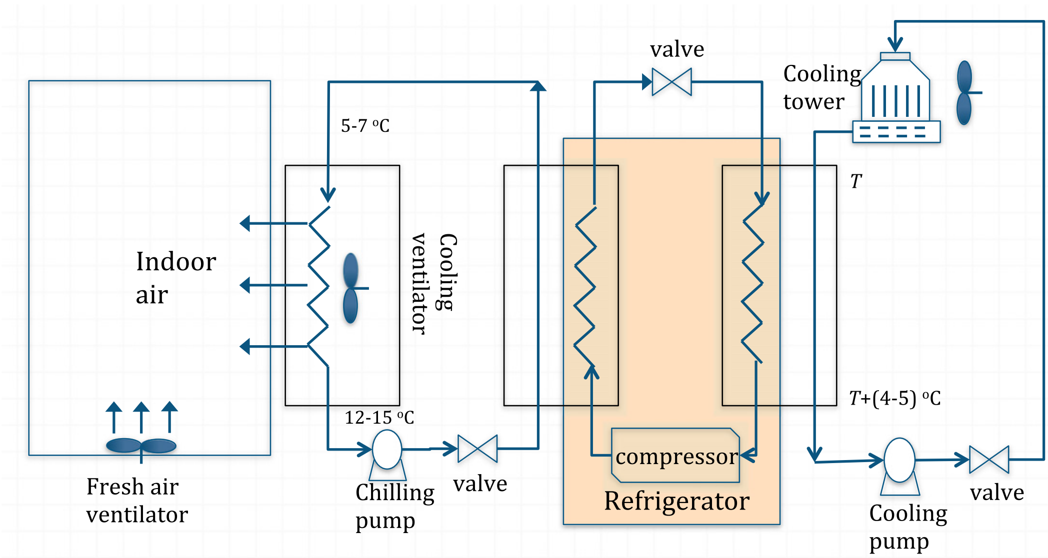

Fig. 1. Major energy consuming facilities in a HVAC system.

energy consumption of HVAC, we take a closer look at the energy consumption inside the HVAC subsystem.

HVAC system description

The subway HVAC subsystem includes a set of *refrigerators, ventilators, pumps, cooling tower, terminal fans, and the pipes connecting these components.* The typical structure of a subway HVAC system is shown in Fig. 1. Its working routine is as the following:

Working routine of HVAC

The refrigerator is the core of the system. It cools water to 5–7° C, which is called *chilling water* and is carried by the chilling pumps to cool the *supply air*. Then the cooled supply air will be blowed by the supply fans and the terminal fans into building to cool the indoor air. Once after cooling the supply air, the temperature of the chilling water increases to about 12–15° C, which will be returned to the refrigerator. This is the heat exchange circle to cool the indoor air.

At the cooling tower side, the cooling pump carries the *cooling water* from the cooling tower to the refrigerator to cool the indoor air. The refrigerator sends back water with temperature increased about 4–5°C to the cooling tower, so that the in-taken heat from the indoor air is successfully exchanged from the refrigerator to the outside.

Note that there is also a *fresh air ventilator*, which is responsible to blow outdoor fresh air into the subway station. It on the one hand maintains indoor air quality (such as reduce CO_2 density) and on the other hand cools the indoor air when the outdoor temperature is lower than the indoor temperature. The studies on subway indoor air quality control can be referred to Liu et al. (2013), Kim et al. (2012).

Table 1 illustrates further the number of different facilities and their rated powers in a HVAC system in a subway station. It can be seen that the refrigerators have obvious higher rated power than the other components. But because the operation of HVAC is complex, the runtime energy consumption of HVAC can be much different from the rated power. An investigation to disaggregate the runtime consumption in HVAC system is therefore conducted.

Disaggregate the energy consumption of HVAC

For the HVAC system, energy consumption was disaggregated into the consumption of 1) refrigerators, 2) ventilators, 3) pumps, 4) cooling towers and 5) terminal fans. Note that the HVAC systems in different stations have similar hardware structure.

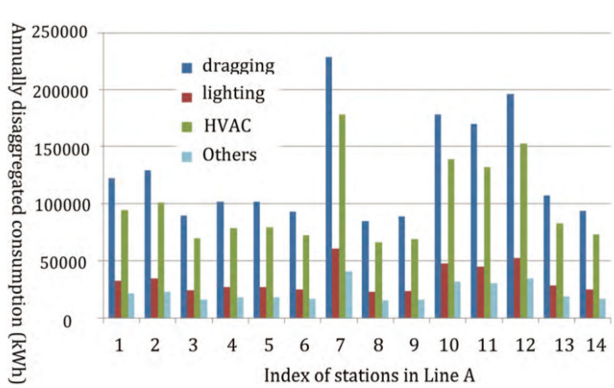

Fig. 2. Disaggregated annual energy consumption of subway stations in Line four (kWh).

Table 1
Main components in a subway HVAC and parameters.

Device names		Rated power (kWh)	Number of devices
Refrigerator	Large refrigerator	212	2
	Small refrigerator	68	1
Chilling water pump	Large pump	30	4
	Small pump	11	2
Cooling water pump	Large pump	30	4
	Small pump	11	2
Main ventilators	New-air supply fan	90	2
	Return fan	90	2
Terminal fans	Terminal 1–17	1.1–7.5	17

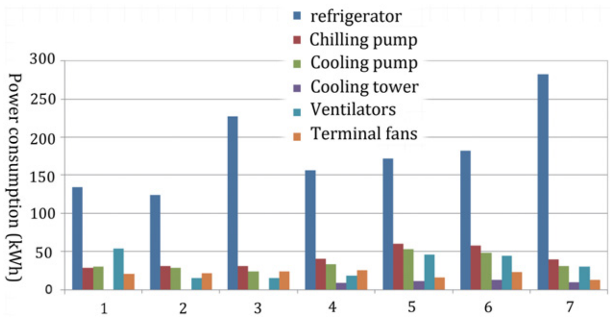

Fig. 3. Disaggregated daily energy consumption of HVAC subsystems in seven stations.

Table 2
Notations defined for the load and supply models.

Notations	Definitions
$L(t)$ (kJ)	The quantity of thermal imported from outside to inside at t
$T(t)$ (^oC)	The indoor temperature at t
$T_o(t)$ (^oC)	The outdoor temperature at t
R_{eq}	Heat transferring resistance from outside to inside
M_{air} (m^3)	The volume of outdoor air input into the subway station
c	Volumetric heat capacity of air
T_p (^oC)	The body temperature of passenger
$n(t)$	The number of passengers at time t
M_{mix} (m^3)	Volume of mixed air
M_{new} (m^3)	Volume of new air
M_{ac} (m^3)	Volume of cooling air
α	The proportion of new air in the mixed air
T_{ac} (^oC)	Temperature of cooling air at the outlet of refrigerator
T_{mix} (^oC)	Temperature of the mixed air
e_{ac}	Efficiency of the cooling air transportation
M_z (m^3)	The volume of air inside the subway station

Fig. 3 shows the average disaggregated daily consumption of different facilities in the HVAC systems in seven stations of line A in August 2013. For a more clear interpretation, Fig. 4 compares the portions of energy consumed by different facilities. The results indicated that the refrigerators took the greatest potion, which was 50%; the pumps took 29%. Since the pumps must be started together with the refrigerators, so that the consumption of the refrigerators and pumps are counted together as the *cooling part consumption*. Overall, the cooling part consumption includes the refrigerators, cooling pumps, chilling pumps, and cooling tower, which take more than 80% of the total consumption. So that the essential problem is how to reduce the consumption of the cooling part.

Investigate the load and supply relationship

To find an efficient way to save energy, we conducted deliberately sensor deployment and data analysis to investigate the interplay between the cooling supply and the heating load in subway HVAC system. The heating load includes heat brought by passengers, air flow, and radiation from outdoor to indoor, whose sum is called the *heating load* of the HVAC system. To keep the indoor temperature at a desired setting point, the HVAC system must supply appropriate cooling capacity, called *cooling supply* to response to the *heating load*. By a comprehensive data collection and carefully analysis, we show that the heating loads have distinct and predictable signatures in working days and weekends, which provide important evidence for designing energy efficient control policies.

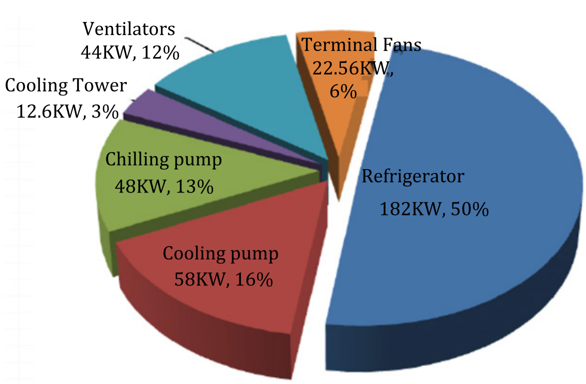

Fig. 4. Energy partition of HVAC subsystem in summer seasons.

Sensor deployments

In stations S_1, S_2 and S_3 of line A, we deployed different kinds of sensors and smart meters to monitor the indoor, outdoor temperatures, passenger flows and power consumption of the HVAC systems in real-time. We give notations in Table 2 to list the parameters which are used to characterize the heating load. Some of the parameters are directly monitored and some of them will be inferred lately by our proposed load signature model.

In each station, four temperature sensors were installed inside and two sensors were deployed outside the subway to monitor the indoor and outdoor temperatures $T(t)$ and $T_o(t)$ respectively. $T(t)$ is calculated by averaging the readings of four indoor sensors. $T_o(t)$ is the average of two outdoor sensors' readings. CO_2 sensors are installed inside the subway to measure the indoor air quality. The passenger flow is recorded by the ticket checking system, which is denoted by $n(t)$. Note that $n(t)$ is calculated by the sum of the checked-in and checked-out passengers from $t-1$ to t.

Further, temperature sensors were installed at the inlets and the outlets of the refrigerators to measure the temperature of the *return air* $T(t)$ and the *cooling air* $T_{ac}(t)$. Temperature sensors are also installed at the new air pipes and mixed air pipes of the ventilator to measure the temperatures of the *new air* $T_o(t)$ and the *mixed air* $T_{mix}(t)$. Note that the mixed air is the mixing of the return air and the new air. The interpretation of different air flows is shown in Fig. 5. The energy consumption of different components of the HVAC system, i.e, refrigerator, ventilator, water tower, pumps, and fans are measured in real-time by the embedded power meters.

Patterns of the passenger flow

In subway station S_1, from the records of ticket checking system, the variation of passenger flow during one week is shown in Fig. 6. It shows different passenger flow patterns in working days and weekends. In working days there are two obvious peaks in the rush hours. In weekends, the passenger flow was almost uniformly distributed from 8:00 AM to 8:00 PM.

Patterns of the load

How the indoor temperature was affected by the passenger flow and outdoor temperature was also investigated. Fig. 7 shows the joint impacts of the outdoor temperature and the passenger flow to the indoor temperature when the HVAC system was running. It is on a sunny working day. Fig. 7 (a) shows the outdoor temperature in that day. Fig. 7 (b) shows the CO_2 density, which can be used to infer the passenger flow overtime. Fig. 7 (c) shows the variation of the indoor temperature. We can see that: the indoor temperature

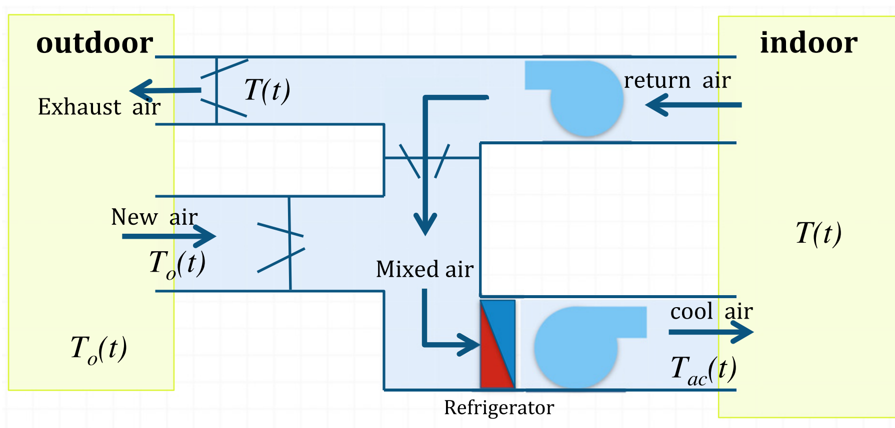

Fig. 5. Air flow in the subway HVAC system.

varied between 22 °C and 27 °C during the day. The indoor temperature curve shows four peaks, whose reason can be explained as the following:

- The first peak at 4:00 AM is because the HVAC system was off at night, so the indoor temperature increases slowly.
- The second peak at 8:00 AM is due to quick heat input by passengers in the rush hours, which is higher than the cooling capacity of the HVAC system.
- The third peak is at 2:00 PM due to the hot outdoor temperature. But this peak is not obvious, because when the outdoor temperature increased slowly, the HVAC had enough time to cool down the indoor air.
- The last peak at 18:00 PM is due to the rush hour in the evening.

The phenomena show intuitively the joint impacts of the environments and the passengers to the indoor temperature. But a quantitative model is still needed to clarify the significances of the environment's impact and the passenger's impact.

Investigate the load signatures of HVAC

Load and supply models

Definition 1 (*load model*). We define the quantity of heat imported from outdoor environments and passengers into the subway station in one time unit as the *load* of the HVAC system in the subway station.

$$L(t) = \alpha_1 \frac{T_o(t) - T(t)}{R_{eq}} + c_p n(t)\,(T_p - T(t)) + \alpha_2 c M_{air}\,(T_o(t) - T(t)) \tag{1}$$

$\alpha_1 \frac{T_o(t)-T(t)}{R_{eq}}$ is the conducted heat, where R_{eq} is the heat conduction resistance from outside to inside. $c_p n(t)(T_p - T(t))$ is the heat brought in by passengers. $\alpha_2 c M_{air}(T_o(t) - T(t))$ is the heat brought in by air exchanging. α_1, c_p, α_2 are unknown parameters determining the portions of heat contributed from different sources. Eq. (1) can be reorganized into:

$$L(t) = \alpha(T_o(t) - T(t)) + c_p n(t)\,(T_p - T(t)) \tag{2}$$

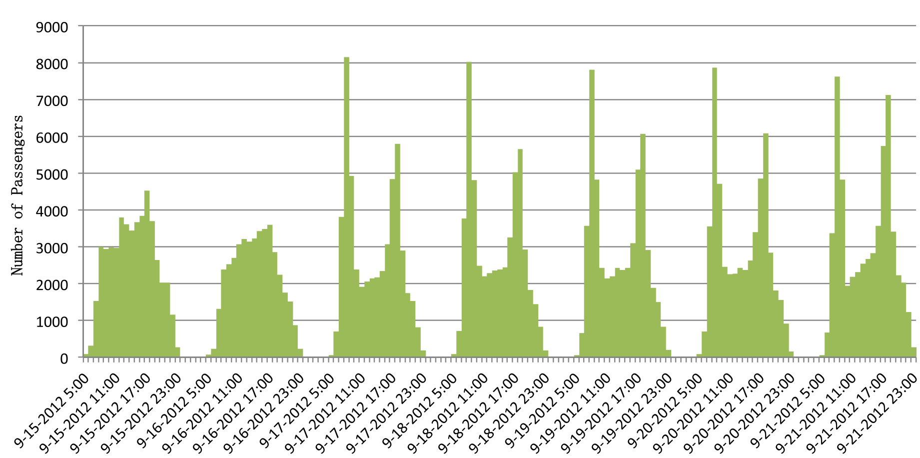

Fig. 6. Pattern of passenger flow over a week.

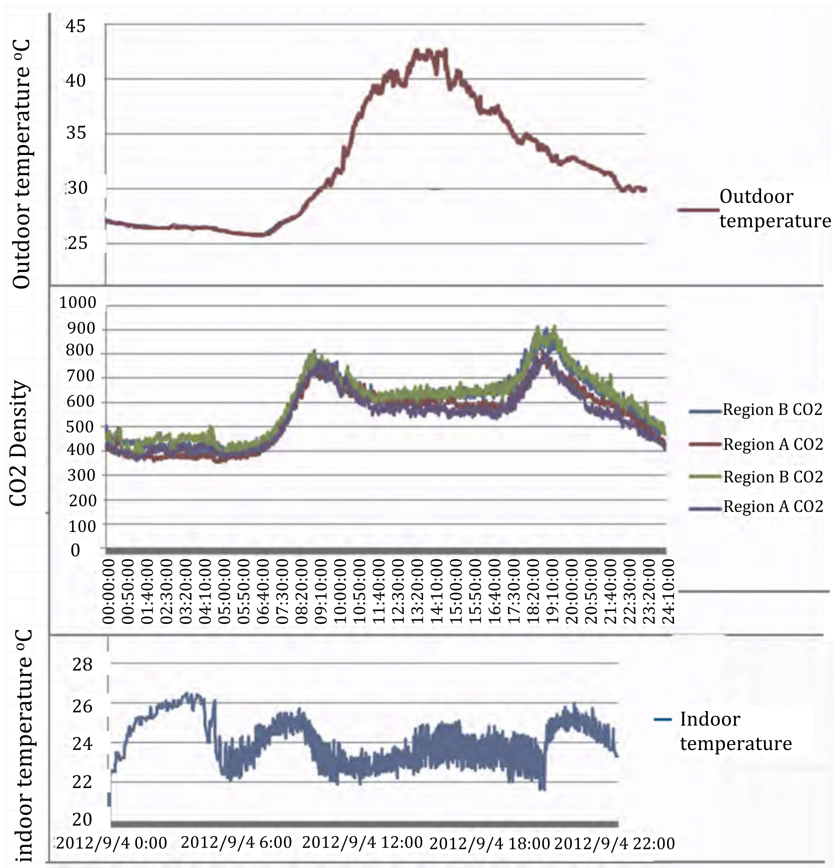

Fig. 7. How the indoor temperature was affected by the outdoor temperature and passenger flow when the HVAC system was running.

where $\alpha = \frac{\alpha_1}{R_{eq}} + \alpha_2 c M_{\text{air}}$ indicates the coefficient of the heat input by indoor-outdoor temperature difference. α and c_p will be learned by sensing data. Note that this model assumes that the heat input by passengers is proportional to the number of passengers and the temperature difference between the passenger body and indoor air.

The HVAC system responses the loads to control the indoor temperature. By assuming that the indoor air is fully mixed, the variation of indoor temperature is mainly caused by the thermal difference of the load and the supply:

$$L(t) - S(t) = cM_z \Delta(t) \tag{3}$$

where M_z is the volume of air in the subway station, which can be calculated by the geometrical information of the station. $\Delta(t) = (T(t+1) - T(t))$ is the temperature difference from time t to time $t+1$.

Definition 2 (*supply model*). The quantity of heat cooled down by the HVAC system in a unit time is defined as the *supply* of the HVAC system, which is defined based on the different working modes of the HVAC system (Wang et al., 2014):

$$S(t) = \begin{cases} cM_{new}\,(T(t) - T_o(t)), & \text{New air mode} \\ (T^w_{in}(t) - T^w_{out}(t))\, V^w_{cool}\beta_{ac}, & \text{Refrigerator mode} \\ cM_{new}\,(T(t) - T_o(t)) + (T^w_{in}(t) - T^w_{out}(t))\, V^w_{cool}\beta_{ac}, & \text{Mixed} \end{cases} \tag{4}$$

where M_{new} is the volume of new air blowed into the subway station by the new air ventilator per time unit. $T^w_{in}(t) - T^w_{out}(t)$ is the temperature difference of input and output water at the refrigerator; V^w_{cool} is the volume of the cooling water; β_{ac} is an unknown parameter, which is determined by the proportion of cooling contribution of the refrigerators. It will also be learned from the sensing data. $(T^w_{in}(t) - T^w_{out}(t))\, V^w_{cool}\beta_{ac}$ measures the cooling supply provided by the refrigerator and $cM_{new}(T(t) - T_o(t))$ measures the cooling supply of the new air.

From the fan affinity laws (Ford, 2011), the air volume delivered by a ventilator is proportional to the one-third order of the ventilator's operating power: $M_v = \beta_v E_v^{\frac{1}{3}}$. So that, the supply model of the HVAC system in the subway station can be rewritten into:

$$S(t) = \begin{cases} cE_v^{\frac{1}{3}}\beta_v\,(T(t) - T_o(t)), & \text{New air mode} \\ (T^w_{in}(t) - T^w_{out}(t))\, V^w_{cool}\beta_{ac}, & \text{Refrigerator mode} \\ cE_v^{\frac{1}{3}}\beta_v\,(T(t) - T_o(t)) + (T^w_{in}(t) - T^w_{out}(t))\, V^w_{cool}\beta_{ac}, & \text{Mixed} \end{cases} \tag{5}$$

In the load and supply model, $T_o(t), T(t), T^w_{in}(t), T^w_{out}(t)$, E_v and V^w_{cool} are measured in real time by the deployed sensors. α, c_p, β_{ac} are unknown.

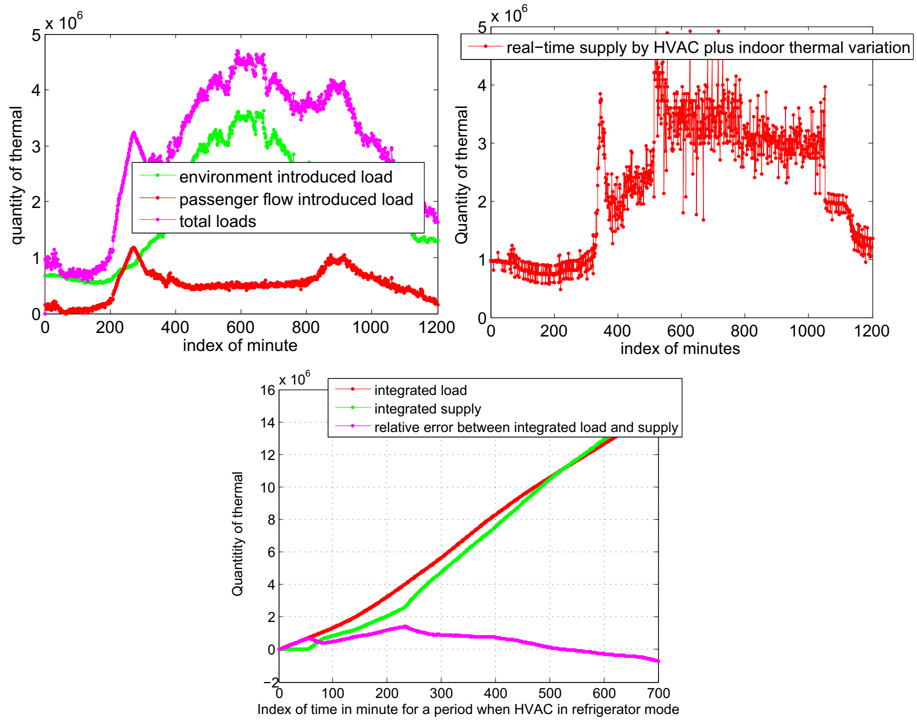

Fig. 8. Derived load signatures vs. variation signatures of supply vs. the relative error between integrated load and integrated supply.

Identify load signature by linear regression

Linear regression model

By substituting Eqs. (1) and (5) into Eq. (3), we construct a linear regression model to estimate the unknown parameters:

$$\begin{bmatrix} n(t)\,(T_p - T(t)) \\ T_o(t) - T(t) \\ V^w_{cool}\,(T^w_{in}(t) - T^w_{out}(t)) \end{bmatrix}^T \begin{bmatrix} c_p \\ \alpha \\ -\beta_{ac} \end{bmatrix} = cM_z\Delta(t) \tag{6}$$

Eq.(6) can be rewritten as $\mathbf{A}(t)\theta = \mathbf{B}(t)$. Then by sensor measurements and HVAC states from 1 to t, we can set up an overdetermined observation matrix $\mathbf{A}_{1:t} = [\mathbf{A}(1), \mathbf{A}(2), \cdots, \mathbf{A}(t)]^T$, and a measurement vector $\mathbf{B}_{1:t} = [\mathbf{B}(1), \mathbf{B}(2), \cdots, \mathbf{B}(t)]^T$. Then the problem of identifying the load signature is to identify the vector θ by solving $\mathbf{A}_{1:t}\theta = \mathbf{B}_{1:t}$, with the constraints that c_p, α, β_{ac} are nonnegative.

In our early work, we have provided a public online dataset about the environment and energy consumption information of the HVAC systems of three subway stations in August and September 2013 (Wang et al., 2013). The dataset provides real-time $T(t)$, $T_{ac}(t)$, $T^w_{in}(t)$, $T^w_{out}(t)$, V^w_{cool}, and E_v in one-minute resolution. The passenger flow data is in per-hour resolution. We estimated the per-minute passenger amount by linear interpolations. The data collected from S_1 from a timespan of Aug 21st, 2013 to Aug 23rd, 2013 in the dataset was selected to solve the linear regression model. Since the coefficients are required to be nonnegative, directly applying the least square estimation is inefficient. In Wang et al. (2014), we have developed a search algorithm to find the coefficients that best match the integrated supply and integrated load.

Load signatures of subway HVAC

By using data of August 23, 2013, the calculated optimal load parameter for station S_1 is θ is $[83, 53703, -1290071]^T$. The parameters change slightly with variation of the scope of the data. By substituting the calculated coefficients into the load model, the derived load signature was plotted in Fig. 8a). The real-time supplies calculated by the supply model are plotted in Fig. 8b). We can see that the supply follows closely to the load. The relative error between the integrated load and integrated supply is plotted in Fig. 8c), which is relatively small. It indicates that the searching algorithm has provided a rather confident estimation to the load signatures. From the load signature, we can see that:

1. The loads contributed by the outdoor temperature take the major portion, more than the thermal loads introduced by the passengers.
2. The load signature in a day is predictable according to the outdoor temperature and traffic flow pattern.
3. The heating load increases quickly in the rushing hours, causing three peaks during a day, i.e., two peaks at rushing hours and one at the hottest time at noon.

Learned insights for energy saving

From the energy disaggregation, sensor readings, and the identified load signature of the HVAC system, we learned valuable insights and potential points for energy saving in the HVAC systems in subways.

1. In current (time-table based) control strategy, the indoor temperature is sometimes lower or higher than the desired temperature, because of the mismatching of supply and load. An energy efficient control strategy should be adaptive to the real-time load.
2. The conventional HVAC control strategy has not taken the variations of the passenger flow into consideration.

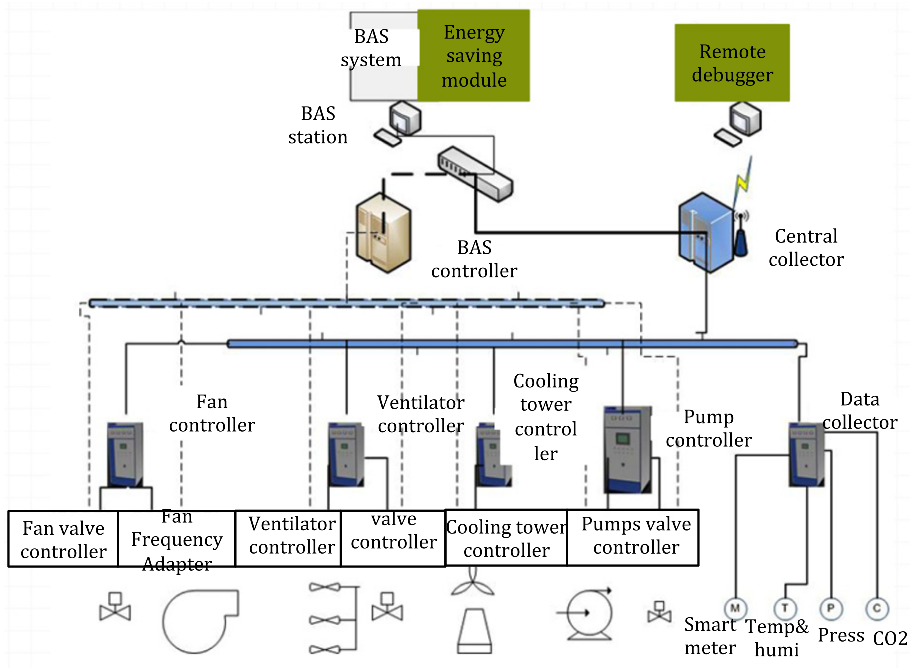

Fig. 9. System architecture of autonomous HVAC control systems.

3. The amount of fresh-air supply is not adapting to the indoor-outdoor temperature difference. In conventional control strategy, the fresh-air supply is adjusted only once a season, whose control unit is not connected to the automation system.
4. The pumps are overused. In the field study, we found that the number of running pumps is generally larger than the designed number. The reason was found that the valves of the refrigerator pipes were not jointly controlled (not shut down) when the refrigerator was turned off.

Autonomous HVAC control system

Based on the learned insights for energy saving and the load signatures of the HVAC systems, we designed and developed autonomous HVAC control system from January 2013 to May 2013, in a pilot project supported by Hongkong MTR, particularly in three metro stations in line *A*. We introduce the system design by using S_1 station as an example.

Design principles

The principle of the control system design is that: 1) to use the existing facilities in the old system as much as possible to reduce the updating cost; 2) the autonomous control system should coexist with the old control system and supports easy switch for the purpose of system reliability; 3) we exploit the idea of *distributed control, centralized management*, i.e., the ventilators, pumps, and refrigerators are controlled distributively for subsystem reliability. A central controller is responsible to monitor overall system states and set control parameters to the distributed controllers. 4) reliability: all the control devices need to work well under the hostile environments in the subway station.

System architecture

The architecture of the developed autonomous HVAC control system is shown in Fig. 9. The key parts are: *central controller*, *distributed controller*, *sensors*, *electric valves*, and *frequency adapters* to enable autonomous control of the HVAC systems.

i). *Controllers*: There are five distributed control cabinets (DCC): i.e., *ventilator cabinet, cooling pump cabinet, freezing pump cabinet, refrigerator cabinet, and cooling tower cabinet*, and one *central control cabinet*(CCC). All DCCs are connected to the CCC via Profibus. Each DCC contains information collection unit, logic unit, and failure protection unit, working individually in run-time to control its HVAC facility (such as ventilator). Such a distributed design is to avoid the system failures in case the communication failures happen to improve the system reliability. The central controller makes higher level decisions and assigns control parameters to the DCCs. The CCC is connected to the building automation system (BAS), in which, a graphical user interface is provided to render the run-time states of the HVAC system to the subway station managers.

ii). *Sensors and Data collection Unit:* As mentioned in Sensor Deployments section, we deployed temperature, humidity, CO_2 sensors to monitor environment states. We also deployed temperature sensors and smart meters to monitor the working states of the HVAC system. The passenger flow data is obtained from the ticket checking system. The sensor data are reported to the central controller via profibus links.

iii). *Electric valves and frequency adapters.* We added electric valves to the pumps, so that the valves can be jointly controlled with the refrigerators and the ventilators. Variable frequency drives were added to the pumps, so that the pumps can adjust water flow by frequency change, which can smooth the switching of pumps when the working states of the refrigerators change.

Autonomous control policies for energy saving

Based on the hardware architecture, we designed autonomous control policies for the HVAC system. For considerations of practical issues, we designed and developed rule-based, adaptive control policies. These rule-based policies for different HVAC subsystems are

Table 3
Control policies for different components of the HVAC system.

Components	Autonomous control	Sensors and control units	Control policies
Refrigerator	Autonomously controlled stop and start	Indoor temperature, humidity, outdoor temperature, humidity	*Start-stop policy*: Start a refrigerator when outdoor air's enthalpy value (Chu et al., 2005) > (52 KJ/kg) +(3 KJ/Kg); Stop all refrigerators when the outdoor air's enthalpy value< (52 KJ/kg) -(3 KJ/kg). *Add-decrease policy:* When cooling water temperature > 7^oC + 1^oC and when the load of running refrigerators is higher than 95%, start an additional refrigerator. When the cooling water temperature< 7^oC and when the average loads of the refrigerators is lower than 50%, stop one refrigerator. *Timely scheduled policy:* In working days, start a refrigerator at 7:30 AM, if no refrigerator has been started and enthalpy value > (52 KJ/kg) -(3 KJ/kg).
Valves of pipes	Autonomous stop and start	Electrical valves	*Start-stop policy*: Before starting a refrigerator, open its valves of the cooling water pipes and chilling water pipes; Stop the valves of the pipes after stopping the refrigerator.
Cooling pumps. (Chilling pumps is the same)	Jointly controlled with refrigerator and frequency adapting	Frequency adapter, inlet and outlet temperature sensors	*Frequency Policy*: Frequencies ofall running cooling pumps are set equal. When the frequency of the running cooling pumps is higher than the setting frequency + 5 Hz, start another cooling pump. When frequency of the running pumps is lower than the setting frequency - 10 Hz, stop a cooling pump. *Jointly control with refrigerator*: Start a cooling pump before starting a refrigerator, if the number of running cooling pumps is not more than the number of running refrigerators. Turning off the cooling pumps by frequency policies after a refrigerator is turned off.
Cooling tower ventilators	Autonomous stop and start and gear adaptation	Cooling water temperature sensor	*Gear level setting*: 1 low→ 2 low → 3 low →4 low →1 high+ 3 low →2 high+2 low →3 high+1 low →4 high *Gear level adapting policy:* When returned water temperature> *max*(32^oC, wet-bulb temperature) Hordeski (2011) for 5 min, increase a level; when returned water temperature< *max*(20^oC, wet-bulb temperature) Hordeski (2011) for 5 min, decrease a level.
Ventilators	Autonomous stop and start, frequency adapting, value jointly control	CO2, temperature, humidity, outdoor temperature, humidity, electrical valves	*Operating modes:* 1) new air mode when refrigerators are off, the new air valve is fully open; 2) mixed mode, when both new air ventilators and refrigerators are used, the new air value is partially open; the supply fan and exhausted fan are open; 3) winter ventilation mode: the new air value is partially open, the working frequency is low. *Enthalpy value based running mode selection:* 1) Working in mode 1, when (39 KJ/kg) +(3 KJ/Kg)<outdoor air's enthalpy value<(52 KJ/kg) -(3 KJ/Kg); 2) turn to mode 2 when outdoor air's enthalpy value>(52 KJ/kg) +(3 KJ/kg); 3) turn to mode 3 when outdoor air's enthalpy value<(39 KJ/kg) - (3 KJ/kg).

summarized in Table 3. Since the polices are depicted in detail in the table, we only explain some key points here:

1. The air enthalpy value (Hordeski, 2011) measured the amount of heat in a unit volume of air, whose formula is:

   $$i = 1.01t + (2500 + 1.84t) * 0.001d \tag{7}$$

   where $t = T(t) + 273.15$ is the air temperature and d is the water content in 1 kg air. The air enthalpy was calculated in real-time based on sensor readings to indicate the thermal condition of the air.
2. For appliances with frequency adapter, the running frequency is measured as an indicator of the loads to decide whether to start an additional one or to stop a running one.
3. The wet-bulb temperature (Chu et al., 2005) is the lowest temperature that can be reached under current ambient conditions by the evaporation of water, which is the temperature felt when the skin is wet and exposed to moving air. It is determined by current temperature and humidity.

By using the air enthalpy, water temperature, running frequency of the devices as the indicators of the system loads, the rule-based control policies have enabled an autonomous and adaptive control strategy for the HVAC system, which makes the supply of the HVAC be adaptive to the load variations. Note that the policies in Table 3 is the result after many online test and evaluations. Currently, the predictive control is only reflected by the conditionally (by both time and rule) starting of a refrigerator in the morning before the rush hour. More intelligent predictive control relies on the accurate load prediction, which is currently difficult because it needs more information such as the weather, social events knowledges, and more powerful information fusion strategies. At current stage, we present the combination of rule-based and adaptive strategy, which is reliable, needs much less information, and is practical.

Implementation of hardware and software systems

We spent four months to develop and implement the proposed autonomous HVAC control systems in three subway stations in line A of Beijing. During the system development and implementation, we have encountered and solved numerous practical problems. Since the subway system cannot be disturbed during the system development, most of the development work were carried out at mid-night when the trains were not running. We must guarantee that the original control system can work normally in every morning after our development at night, therefore, the autonomous control system was designed to coexist with the original control system. The control strategy can be easily switched between each other.

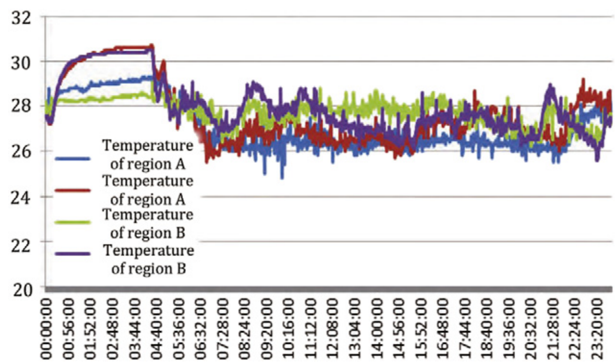

Fig. 10. Temperature variations during a day on August 23, 2013. Each region has two sensors.

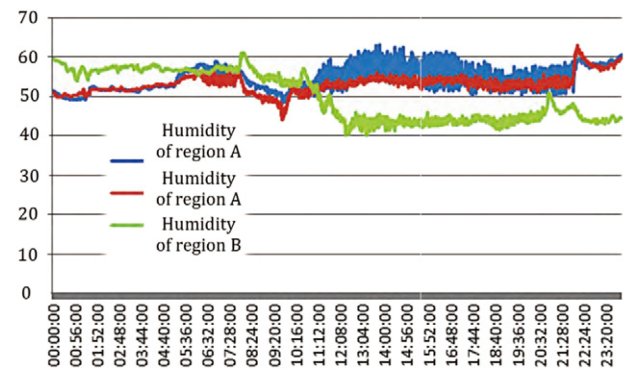

Fig. 11. Relative humidity variations during a day in August 23, 2013. Region A has two sensors.

Hardware system

The HVAC appliances used in the subway stations are from Carrier. We developed the central controller and the distributed controllers as introduced in Section V-B and deployed the Profibus DP network to connect these control cabinets to the HVAC appliances. These control units collect real-time working states from the HVAC, make local decisions and deliver the control commands. All information are collected and transferred by Profibus DP network.

Software system

Based on the deployed sensors and the control units, we developed and deployed software systems to monitor the working states of the HVAC system and to render the system states to the users. The software was deployed as a plug-in of the Building Automation System (BAS), which runs on the BAS server. It provides comprehensive, real-time environment and working states information of the HVAC system, which not only provides real-time information for system state monitoring and performance evaluation, but also provides important evidence for verifying and online diagnosing the control policies.

Energy saving performance

The developed autonomous HVAC control system has worked well during the summer of 2013. The control performances and the energy saving performances were evaluated.

Control performance

The temperature variations are evaluated to judge the portion of temperatures within the comfort interval.

Comfort interval

Because passengers stay only short time in the subway station, the comfort interval in the subway stations is looser than that in home or in commercial buildings. The interval between 25°C to 29°C is set as the comfort temperature interval and 40%–60% is set as the comfort humidity interval. Fig. 10 shows the temperature variations during a day in station S_1. The four curves show the readings of four temperature sensors in the subway station. We can see the indoor temperatures from 5:00 AM and 11:00 PM are well controlled in the comfort interval. Fig. 11 shows the humidity variations of the same day in the same station, which shows that the indoor humidity was also well controlled to be within the comfort interval.

Temperature peaks

The temperature variations in Fig. 10 show that when the HVAC system was stopped at night the indoor temperature increased quickly. There were slight temperature peaks around 8:00 AM because the quick heating load increment at the rushing hours. Anyhow, the overall performances for temperature and humidity control are satisfactory.

Respond speed

We also evaluated how the indoor temperature was affected by the cooling air temperature. Fig. 12 shows the responses of indoor temperature following the variations of the cooling air. It indicates that when the temperature of the cooling air changes, the indoor temperature changes quickly, with a delay of ten minutes level.

Adaptivity of the refrigerators

We further investigated how the working states and energy consumptions of the refrigerators change over a day. Fig. 13a) shows the temperature variations and indoor-outdoor temperature differences over a day. Fig. 13b) shows the energy consumption of the two refrigerators respectively in that day. We can see that the working loads of the refrigerators respond quickly and proportionally to the indoor-outdoor temperature differences.

Energy saving performance

The energy saving performances of the autonomous control system were evaluated by the energy logs in August 2013, which was the hottest time in Beijing. Since the autonomous control system coexists with the conventional control system, we selected three days to run the conventional control strategy, and ran the autonomous control strategy in the other days. The three days in which we ran the conventional control policy were highlighted in Table 4. Note that $T_o(t)$ and $T(t)$ in the table are average outdoor and indoor temperature over the day.

Energy consumption depends on the outdoor temperature

At first, we can see that the energy consumptions of the HVAC system in a day highly depend on the average outdoor temperature in that day. The fifth column of the table shows the average outdoor temperature from 8: 00 AM to 10: 00 PM during the day and the sixth column shows the average indoor temperature of the same duration. We can easily see that the daily energy consumption of the HVAC system is positively correlated to the average outdoor temperature.

Energy saving performance

We select the days that had similar outdoor temperatures to compare the energy consumptions of the conventional and the

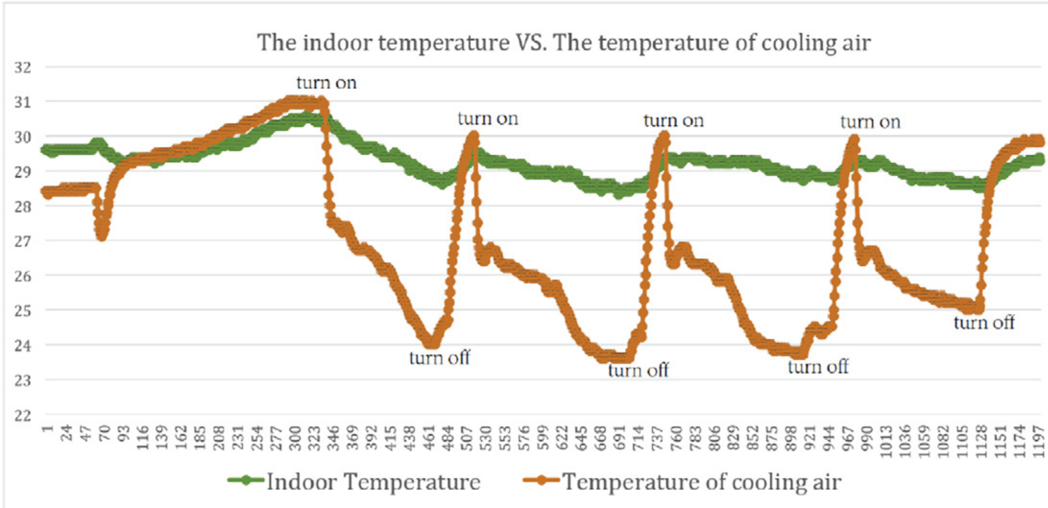

Fig. 12. How the indoor temperature response to the cooling supply of the HVAC system.

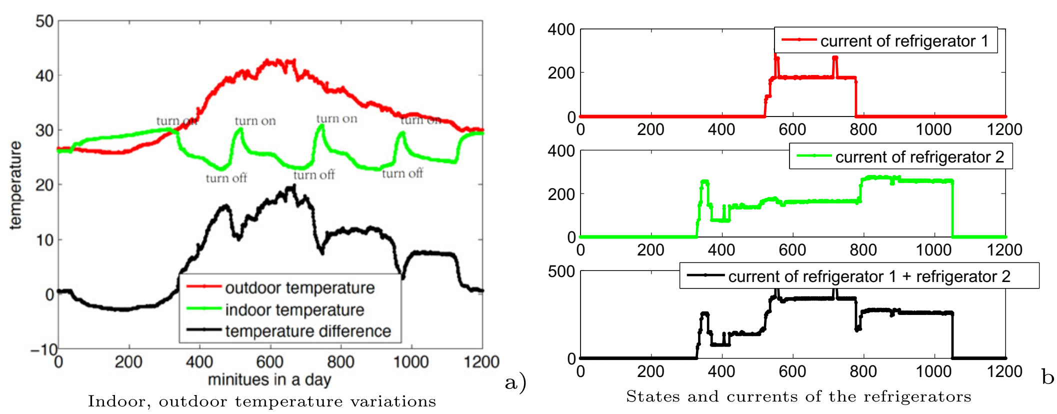

Fig. 13. Indoor outdoor temperature differences vs. the states and the consumption of the refrigerators.

autonomous running modes. In particular the energy consumptions of August 8 and August 13 of the old control strategy were compared with that of August 11, August 14, and August 16 of the autonomous control strategy. The energy consumption of August 22 was compared with August 20, 21, and 24. The energy saving performance of the autonomous control policy over the conventional control policy is shown in Table 5. From the results, it can be seen that, for example, in S1, the autonomous control system can save more than 2000 kWh power per day. The average energy saving ratio in S1 is over 38%, in S2 is over 19% and in S3 is over 32%.

Table 4
Energy consumption comparison.

Time	S_1	S_2	S_3	$T_o(t)$	T(t)	Mode
7	4644	5928	7923	28.38	29.19	Auto
8	6859	5850	10,213	31.52	29.21	Conventional
9	5757	9897	13,580	33.03	29.56	Auto
10	6766	6777	6484	33.85	29.84	Auto
11	3797	7475	6772	31	29.6	Auto
12	4950	7083	10,167	30	29.3	Auto
13	6673	10,554	12,782	31.24	27.99	Conventional
14	5603	6987	7742	31.52	28.15	Auto
15	4829	6504	8130	33.53	30.15	Auto
16	5482	5518	6252	30.96	30.32	Auto
17	7639	7715	10,464	36.32	28.74	Auto
18	7569	7126	6636	33.07	28.74	Auto
19	7142	7265	7462	32.63	28.48	Auto
20	4869	5487	7927	29.99	28.79	Auto
21	5794	5608	6580	29.48	28.86	Auto
22	10,313	7381	8992	29.45	27.59	Conventional
23	5058	4115	4803	32.07	28.45	Auto
24	5598	4966	4825	29.95	28.5	Auto

Energy reduction than August 2012

Despite the weather differences, we compared roughly the average energy reduction in August 2013 than August 2012. The sum

Table 5
Energy saving performance of autonomous control.

Station names	S_1	S_2	S_3
Average of Aug. 8,13 in old mode	6766.84	8202.7	11,497.95
Average of Aug. 11, 14 in auto mode	4700.5	7231.8	7257.30
Saved energy	2066.341	970.9	4240.64
Energy saving ratio	0.305	0.118	0.368
Average of Aug. 22 in old mode	10,313.89	7381.17	8992.21
Average of Aug. 20,21,24, auto	5420.62	5353.97	6444.54
Saved energy	4893.26	2027.20	2547.67
Energy saving ratio	0.474	0.274	0.283
Average energy saving ratio	0.389	0.196	0.326

Table 6
Average energy saving performance in August.

Stations	27 day consumption in August 2012 (kWh); Average temperature in the duration is 22.5–33.3	27 day consumption in August 2013 (kWh), Average temperature in the duration is 23.1–34.2	Energy saving ratio
S1	152,000	122,310	19.5%
S2	218,123	177,227	18.7%

energy consumption of 27 days in which autonomous control policy was applied in August 2013 was compared with the same period consumption in August 2012. Table 6 shows the average energy saving in August for stations S_1 and S_2. Despite the weather difference, the roughly estimated average energy reduction ratio is around 19%, which is impressive for the large base of daily consumption. Since the HVAC system works four months in a summer, it not only makes the subway more environment friendly, but also brings tangible economic benefit to the operating company via reducing the operating cost.

Conclusion

We have presented the energy disaggregation approach, load signature identification and, an autonomous HVAC control system for saving energy in HVAC systems of subway stations. The field analysis shows that HVAC consumes 31%–40 % energy in the overall energy consumption of a subway station. Among the consumption of the HVAC, the refrigerators and the pumps take the greatest portion. The load signatures according to the variation of outdoor temperature and passenger flows were identified. To save energy, autonomous control system was developed and rule-based control policies were carefully designed by online tests and evaluations. Onsite experiments showed that the autonomous control system improved the adaptivity of the HVAC system and saved energy for 20% to 38% in different stations. In future work, if the prediction of the outdoor environment and the passenger flow can be more accurate, prediction-based HVAC control is an important direction to further reduce energy. Autonomous control devices and standards are also open to be explored.

Acknowledgments

This work was supported in part by the National Natural Science Foundation of China grant nos.11671400,61672524; the Fundamental Research Funds for the Central University, and the Research Funds of Renmin University of China,2015030273.

References

Anon, Sustainable energy management for underground stations.2011, http://seam4us.eu.
Anon, Beijing subway. Wikipedia, 2013.
Al-Sallal KA. A review of buildings' energy challenges. Int J Environ Sustain 2014;3(1). Aug.
Andrews C, Yi D, Krogmann U, Senick J, Wener R. Designing buildings for real occupants: an agent-based approach. IEEE Trans Syst Man Cybern Part A Syst Humans 2011;41(6):1077–91.
Awad AHA. Environmental study in subway metro stations in Cairo, Egypt. J Occup Health 2002;44(2):112–8.
Casals M, Gangolells M, Forcada N, Macarulla M, Giretti A. A breakdown of energy consumption in an underground station. Energ Buildings 2014;78:89–97.
Chu C, Jong T, Huang Y. A study of thermal comfort control using least enthalpy estimator on HVAC system. American control conference, 2005. Proceedings of the 2005. vol. 5. 2005. p. 3665–70.
Fong K, Hanby V, Chow T. HVAC system optimization for energy management by evolutionary programming. Energ Buildings 2006;38(3):220–31. Mar.
Ford RW. Affinity laws. ASHRAE J 2011;53(3):42–3.
Fulkerson W, Levine MD, Sinton JE, Gadgil A. Sustainable, efficient electricity service for one billion people. Energy Sustain Dev 2005;9(2):26–34. June.
Giretti A, Carbonari A, Vaccarini M. Energy saving through adaptive control of ventilation systems. Gerontechnology 2012;11(2). June.
Gungor V, Lu B, Hancke G. Opportunities and challenges of wireless sensor networks in smart grid. IEEE Trans Ind Electron 2010;57(10):3557–64. Oct.
Hordeski MF. HVAC Control in the New Millennium. CRC Press.; 2011.
House J, Smith T. Optimal control of building and HVAC systems. American control conference, proceedings of the 1995. vol. 6. 1995. p. 4326–30. vol. 6.
Hu Z, Li X, Zhao X, Xiao L, Wu W. Numerical analysis of factors affecting the range of heat transfer in earth surrounding three subways. J China Univ Min Technol 2008;18(1):67–71. Mar.
Kelman A, Ma Y, Borrelli F. Analysis of local optima in predictive control for energy efficient buildings. 2011 50th IEEE conference on decision and control and european control conference (CDC-ECC). 2011. p. 5125–30.
Kim M, SankaraRao B, Kang O, Kim J, Yoo C. Monitoring and prediction of indoor air quality (IAQ) in subway or metro systems using season dependent models. Energ Buildings 2012;46:48–55. Sustainable and healthy buildings.
Lamberts R. Electricity efficiency in commercial and public buildings. Energy Sustain Dev 1996;2(6):49–52. Mar.
Liu H, Lee S, Kim M, Shi H, Kim JT, Wasewar KL, Yoo C. Multi-objective optimization of indoor air quality control and energy consumption minimization in a subway ventilation system. Energ Buildings 2013;66:553–61.
Lu M, He T, Pei X, Chen Z. Analysis of the electricity consumption and the water consumption of Beijing subway. J Beijing JIaotong Univ 2011;35(1):136–9. Feb.
Marzouk M, Abdelaty A. Monitoring thermal comfort in subways using building information modeling. Energ Buildings 2014;84:252–7.
Murayama D, Mitsumoto K, Takagi Y, Iino Y, Yamamori S. Smart grid ready BEMS adopting model-based HVAC control for energy saving. transmission and distribution conference and exposition (T D), 2012 IEEE PES. 2012. p. 1–6.
Palensky P, Dietrich D. Demand side management: demand response, intelligent energy systems, and smart loads. IEEE Trans Ind Inform 2011;7(3):381–8. Aug.
Serban R, Guo H, Salden A. Common hybrid agent platform - sustaining the collective. 2012 13th ACIS international conference on software engineering, artificial intelligence, networking and parallel distributed computing (SNPD). 2012. p. 420–7.
Tashtoush B, Molhim M, Al-Rousan M. Dynamic model of an HVAC system for control analysis. Energy 2005;30(10):1729–45. July.
Teeter J, Chow M-Y. Application of functional link neural network to HVAC thermal dynamic system identification. IEEE Trans Ind Electron 1998;45(1):170–6. Feb.
Wang S, Ma Z. Supervisory and optimal control of building HVAC systems: a review. HVAC&R Res 2008;14(1):3–32.
Wang Y, Feng H, Qi X. SEED: public energy and environment dataset for optimizing HVAC operation in subway stations.2013.
Wang Y, Feng H, Xi X. Sense, model and identify the load signatures of HVAC systems in metro stations. 2014, IEEE PES General Meeting, 2014.
Weidou N, Johansson TB. Energy for sustainable development in China: an overview of approach and work carried out by the working group on energy strategies and technologies of the China Council for International Cooperation on Environment and Development. Energy Sustain Dev 2001;5(4):5–12. Dec.
Yang R, Wang L. Optimal control strategy for HVAC system in building energy management. transmission and distribution conference and exposition (T D), 2012 IEEE PES. 2012. p. 1–8.