On Energy Saving of Subway HVAC System: Investigation and Autonomous Control

Abstract—As the backbone for urban public transportation, subways are also major consumers of energy and 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, impressive 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 had deployed comprehensive environment monitoring, passenger flow monitoring and run-time data logging subsystems to monitor and investigate above features in several metro stations. The extracted features showed a broad space for optimizing the operation of current HVAC systems for energy saving. Based on the insights learned from the field studies, we spent four months to develop and deploy an autonomous HVAC control systems in three metro stations. The system design and deployment were reported. Up to now, the developed autonomous control systems have worked well in the summer season of 2013. The energy logs show that the autonomous control system helped the metro stations reduce energy in a range from 20% to 38% than the conventional control strategy. We also introduce key insights learned for energy saving and some future research directions.

Index Terms—Autonomous control, Sensor network, Air conditioning, HVAC, Energy Efficiency, Sustainability, Power meter

I. INTRODUCTION

The 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 [2], running by two companies, Beijing MTR (operates 14 lines) and Hong Kong MTR (operates 3 lines). It ranks the third in length in the world after Seoul and Shanghai, and serves more than 7.5 millions 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 energy consumptions of Beijing subway was conducted in 2008 [13]. At that time, Beijing subway had only five lines whose daily energy consumptions in April 2008 and in July 2008 are summarized and compared. It showed that the daily energy consumptions of the subway lines ranged from 0.6 million to near 5 million kW·h per day. There was a steep variation of the heating loads. For practical considerations of activity of the HV AC system to match its cooling supply to the variation of the heating loads. For practical considerations of system reliability and the information limitation, we designed rule-based adaptive control strategies and implemented these strategies by deploying control units, frequency adapters, and automatic valves etc. The systems have worked well through the summer season. For energy saving purpose, if it were possible to reduce the energy consumption of the air conditioning subsystems a few percents, impressive quantity of electricity would be saved.

Particularly in three stations ($S_1$, $S_2$, $S_3$) in line $A$, we conducted further research by deploying environment monitoring sensors, smart meters and temperature and state sensors into the HVAC. The passenger flow is recorded by the ticket checking systems. Based on these data, we investigate the run-time features, load and supply signatures of the HVAC subsystems. The study showed that: there were many operating problems in current air conditioning systems in the subway stations, including: 1) the mismatching of loads and supplies; 2) Control is not adaptive to the variation of environments and passenger flows; 3) control problems regarding the pumps and valves etc. To address this problem, we developed an autonomous control system to save energy for 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 field 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 and the information limitation, we designed rule-based adaptive control strategies and implemented these strategies by deploying control units, frequency adapters, and automatic valves etc. 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 remained sections are organized as following. Related works are introduced in Section II. Field studies and investigation to the features of subway HVAC systems are presented in Section III. Load signature investigation is presented in Section IV. Development and deployment of autonomous HVAC systems are presented in Section V and VI respectively.
The energy saving performances are introduced in Section VII. The paper is concluded with discussions in Section VIII.

II. RELATED WORK

The autonomous, optimal control for HVAC systems has attracted great research attentions in the studies of smart and sustainable buildings[12], [17], [6], [18], [10], [22], [14]. The optimal control for HVAC systems in smart building is to determine the optimal solutions (operation mode and setpoints) that minimize overall energy consumption or operating cost while still maintaining the satisfied indoor thermal comfort and healthy environment[19]. This goal is the same in the subway HVAC control systems. Because the HVAC systems contain different types of subsystems, such as gas-side and water-side subsystems, the optimal control problems of HVAC are extremely difficult. One of the difficulties is the lack of an exact model to describe the internal relationships among different components. A dynamic model of an HVAC system for control analysis was presented in [17]. The authors proposed to use Ziegler-Nichols rule to tune the parameters to optimize PID controller. A metaheuristic simulation EP (evolutionary programming) coupling approach was developed in [6], which proposed evolutionary programming to handle the discrete, non-linear and highly constrained optimization problems. Multi-agent-based simulation models were studied in [3] to investigate the performance of HVAC system when occupants are participating. In [22], swarm intelligence was utilized to determine the control policy of each equipment in the HVAC system.

One of the most closely related work is the SEAM4US (Sustainable Energy mAnAgeMent for Underground Stations) project established in 2011 in Europe[1]. It studies the metro station energy saving mainly from the modeling and controlling aspect. Multi-agent and hybrid models were proposed to model the complex interactions of energy consumption in the underground subways[16], [15]. Researchers in this project have also proposed adaptive and predictive control schemes for controlling ventilation subsystems to save energy [8]. But this project lacks the practical implementation.

A. Disaggregation of Annual Energy Consumption

To better understand where has the energy gone in the subway, we conducted a disaggregation approach to the energy consumption, i.e, to divide the overall energy consumption into the consumptions of the dragging system, HVAC, Lighting, and others. Since the investigated line is a newly established line, it provides detailed energy consumption logs of each subsystem in the subway, even the detailed consumptions of the lights in a region. Based on the data logs, the disaggregated annual energy consumptions for the stations of the line are shown in Fig.1.

We evaluated the portions taken by the HVAC system, which were shown ranging from 31% to 40% in different stations. Note that this portion is the portion over a year. Since the HVAC systems work only for 4 months per year in Beijing, i.e, from June to September, the energy consumption of the HVAC systems per day in the summer season are striking. To further understand the energy consumption of HVAC, we take a closer look at the energy consumptions of the HVAC subsystem.

B. Look Closely at the HVAC system

In the subway, the HVAC subsystem is comprised by a set of refrigerators, ventilators, pumps, cooling tower, terminal fans, and the pipes connecting these components. The typical structure of a central HVAC system is shown in Fig.2. The working routine is as following:

1) Working Routine of HVAC: The refrigerator is the core of the system, which cools water to about 5-7 degree. The water will be carried out by the chilling pumps to cool the supply air. The cooled supply air will be blown by the supply fans and the terminal fans into the Fan Coil Units to cool the indoor air. After cooling the supply air, the temperature of the chilling water increases to about 12-15 degree, which will be returned to the refrigerator. On the other hand the cooling pump carries cooling water at about 32 degree from the cooling tower to the refrigerator, and the refrigerator sends back water at about 37 degree to the cooling tower, so that the intaken heat from the indoor air at the refrigerator is successfully exchanged from the refrigerator to the outside.

Another most related work reported the factors affecting the range of heat transfer in subways [11]. They show by numerical analysis that how the heat is transferred in tunnels and stations. Reference [4] studied the environmental characters in the subway metro stations in Cairo, Egypt, which showed the different environment characters in the tunnel and on the surface.

Further than these existing work, we conducted a more thorough and in deep studies on the HVAC systems of metro stations. Not only conducting a comprehensive field study to investigate the distinct features of subway energy consumption, but also are autonomous control systems developed and deployed for the HVAC system in metro stations.

III. FIELD STUDY AND INSIGHTS FOR ENERGY SAVING

We firstly report our field study results and the insights learned for energy saving. In 2012, we collected the electricity billing logs and the logs of AC meters from line A to investigate the energy consumption characters of the subway.

Another most related work reported the factors affecting the range of heat transfer in subways [11]. They show by numerical analysis that how the heat is transferred in tunnels and stations. Reference [4] studied the environmental characters in the subway metro stations in Cairo, Egypt, which showed
new air into the subway station, which on one hand to maintain indoor air quality (such as reduce CO2 density) and on the other hand to cool the indoor air when the outdoor temperature is lower than indoor temperature. Table I further illustrates the number of different facilities and their rated powers in a HVAC system in a subway station. The HVAC system in different stations has similar structure. The real energy consumptions of HVAC can be much different from the rated power, so that we further investigate the disaggregated the energy consumption in a HVAC system.

**TABLE I**

<table>
<thead>
<tr>
<th>Device names</th>
<th>Rated power (kWh)</th>
<th>Number of devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refrigerator</td>
<td>large refrigerator</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>small refrigerator</td>
<td>1</td>
</tr>
<tr>
<td>Chilling water pump</td>
<td>large pump</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>small pump</td>
<td>2</td>
</tr>
<tr>
<td>Cooling water pump</td>
<td>large pump</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>small pump</td>
<td>2</td>
</tr>
<tr>
<td>Main ventilators</td>
<td>new-air supply fan</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>return fan</td>
<td>2</td>
</tr>
<tr>
<td>Terminal fans</td>
<td>terminal T-17</td>
<td>1.1-7.5</td>
</tr>
</tbody>
</table>

C. Disaggregate the Energy Consumption of HVAC

Energy disaggregation investigation for HVAC was conducted in three stations, i.e., $S_1$, $S_2$, $S_3$ in Line A, in which, the energy consumptions of HVAC were further disaggregated into the consumptions of refrigerates, ventilators, pumps, cooling towers and terminal fans. Fig.3 shows the average disaggregated daily consumptions of different facilities in the HVAC systems of seven investigated stations in August of 2012. Fig.4 summarizes the average energy consumptions of the different facilities. The results indicated that the refrigerators took the greatest portion, which was 50%; the pumps took 29%. Since the pumps worked only if the refrigerators were working, so that the consumptions of the cooling part, i.e., the consumptions of the refrigerators, cooling pumps, chilling pumps, and cooling tower took more than 80% in the overall consumption. The investigation motivated us to pay more attention to reduce the consumption of the cooling part.

D. Monitor Environment and Working States of HVAC

1) Load and Supply: In addition to the power disaggregation approach, we conducted deliberately sensor deployment and data analysis to uncover the impacts of the outdoor environments and the passenger flows to the indoor temperature. There are mainly two ways for heat to be transferred into the subway station: 1) the heat transferred from outside and 2) the heat brought in by the passengers. We call the sum of them 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*. Therefore, the signatures of the heating loads is of great importance for designing energy saving control policies.

**TABLE II**

<table>
<thead>
<tr>
<th>Notations</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L(t)$</td>
<td>the quantity of thermal imported from outside to inside at $t$.</td>
</tr>
<tr>
<td>$T(t)$</td>
<td>the indoor temperature at $t$.</td>
</tr>
<tr>
<td>$T_o(t)$</td>
<td>the outdoor temperature at $t$.</td>
</tr>
<tr>
<td>$R_{in}$</td>
<td>heat transferring resistance from outside to inside.</td>
</tr>
<tr>
<td>$M_{air}$</td>
<td>the volume of outdoor air input into the subway station</td>
</tr>
<tr>
<td>$c$</td>
<td>the heat capacity of per cubic air.</td>
</tr>
<tr>
<td>$T_p$</td>
<td>the body temperature of people.</td>
</tr>
<tr>
<td>$n(t)$</td>
<td>the the number of passengers at time $t$.</td>
</tr>
<tr>
<td>$M_{mix}$</td>
<td>volume of mixed air</td>
</tr>
<tr>
<td>$M_{new}$</td>
<td>volume of new air</td>
</tr>
<tr>
<td>$M_{ac}$</td>
<td>volume of cooling air</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>the proportion of new air in the mixed air.</td>
</tr>
<tr>
<td>$T_{ac}$</td>
<td>temperature of cooling air at the outlet of refrigerator.</td>
</tr>
<tr>
<td>$T_{mix}$</td>
<td>temperature of the mixed air.</td>
</tr>
<tr>
<td>$\epsilon_{ac}$</td>
<td>efficiency of of the cooling air transportation.</td>
</tr>
<tr>
<td>$M_z$</td>
<td>the volume of air inside the subway station.</td>
</tr>
</tbody>
</table>

2) Sensor Deployments: In $S_1$, $S_2$ and $S_3$, we deployed different kinds of sensors and smart meters to be indoor, outdoor temperatures, passenger flows and power consumptions of the HVAC systems in real-time. We give notations in Table II to list the parameters to characterize the heating load. Some of the parameters are directly monitored and some of them will be inferred by our proposed load signature model.

We installed temperature sensors at four points inside the subway station and two points outside the subway to monitor the indoor and outdoor temperatures $T(t)$ and $T_o(t)$ respectively. Note that $T(t)$ is calculated by averaging the readings of indoor temperature sensors, so as $T_o(t)$. CO2 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 \( t \).

To monitor the working state of the HVAC system, temperature sensors were installed at the inlets and the outlets of the refrigerators to measure the temperature of the return air \( T_r(t) \) 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 \( T_n(t) \) and the mixed air \( T_{mix}(t) \). Note that the mixed air is the mixing of return air and new air. The energy consumptions of different components of the HVAC system, i.e., refrigerator, ventilator, water tower, pumps, fans etc are measured in real-time by the embedded power meters of the HVAC system. We processed the collected data from sensors to investigate the working signatures of the HVAC system.

3) Monitored Patterns of the Passenger Flow: In station \( S_1 \), from the data of ticket checking system, Fig. 5 shows the variation of passenger flow as a function of time during a week from Sep. 15 to Sep. 21. The passenger flow shows different structure in working days and weekends. In the working days there are two obvious peaks in the rush hours in the morning and in the evening. In week ends, the passenger flow was almost uniformly distributed from 8:00 AM to 8:00 PM.

4) Observed Patten of the Load: Fig. 7 shows how the indoor temperature was jointly affected by the outdoor temperature and the passenger flow 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 CO2 density, which can be used to infer the passenger flow overtime. Fig. 7(c) shows the variation process of the indoor temperature. We can see that: the indoor temperature varied between 22 centigrade and 27 centigrade during the day and there are four peaks in the temperature curve, which can be explained according to following reasons:

- The first peak at 4:00 AM is because the HVAC system was off in the night, so the indoor temperature increases slowly.
- The second peak at 8:00 AM is due to quick heat input by passengers in the rushing hours, which is higher than 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 increases slowly, the HVAC had enough time to cool down the indoor air.
- The last peak at 18:00 PM is due to the rushing hour in the evening.

The measurements show intuitively the joint impacts of the environments and passengers to the indoor temperature. However, we still don’t know the significance of the passenger-introduced load and the environment-introduced load.

IV. INVESTIGATE THE LOAD SIGNATURES OF HVAC

We investigated a quantitative model to more accurately characterize the impacts of environment and the passengers to the thermal load.

A. Load and Supply Models

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

\[
L(t) = \frac{T_o(t) - T_{eq}}{R_{eq}} + n(t) (T_p - T(t)) + c M_{air} (T_o(t) - T(t))
\]  

(1)

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

\[
L(t) - S(t) = c M_z \Delta(t)
\]  

(2)

where \( M_z \) is the volume of air in the subway station, which can be calculated by the geometrical information of the station, such as the length, width, height of the station and the tunnels. \( \Delta(t) = (T(t+1) - T(t)) \) is the temperature difference changed 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 different working modes of the HVAC system:

\[ S(t) = \begin{cases} \begin{align*} c_M \Delta(T_N(t) - T_0(t)), & \text{New air mode} \\ (T_{in}^w(t) - T_{out}^w(t)) V_{cool} \beta_{ac}, & \text{Refrigerator mode} \\ c_M \Delta(T_N(t) - T_0(t) + (T_{in}^w(t) - T_{out}^w(t))) V_{cool} \beta_{ac}, & \text{Mixed} \end{align*} \end{cases} \]  

(3)

where \( M_{new} \) is the volume of new air blown into the subway station by the new air ventilator. \( T_{in}^w(t) - T_{out}^w(t) \) is the temperature difference of input and output at the refrigerator; \( V_{cool} \) is the volume of the cooling water; \( \beta_{ac} = e_{cool} e_{ac} \), where \( e_{cool} \) is the heat capacity of the cooling water and \( e_{ac} \) is the heat transportation efficiency of the refrigerator. So that \( (T_{in}^w(t) - T_{out}^w(t)) V_{cool} \beta_{ac} \) measures the cooling supply provided by the refrigerator and \( c_M \Delta(T_N(t) - T_0(t)) \) measures the cooling supply of the new air.

From the fan affinity laws[7,], ventilators operates under a predictable law that the air volume delivered by a ventilator is in the one-third order of its operating power: \( M = \beta_v E_v^3 \).

So that, the supply model of the HVAC system in the subway station is rewritten into:

\[ S(t) = \begin{cases} \begin{align*} c_{E_v} \beta_v (T_N(t) - T_0(t)), & \text{New air mode} \\ (T_{in}^w(t) - T_{out}^w(t)) V_{cool} \beta_{ac}, & \text{Refrigerator mode} \\ c_{E_v} \beta_v (T_N(t) - T_0(t) + (T_{in}^w(t) - T_{out}^w(t))) V_{cool} \beta_{ac}, & \text{Mixed} \end{align*} \end{cases} \]  

(4)

In the load and supply model, \( T_0(t), T(t), T_{in}^w(t), T_{out}^w(t), E_v \) and \( V_{cool} \) are measured in real time by the deployed sensors. We have provided a public dataset of these sensors’ readings in [20]. Since \( c \) is a known constant. Only \( M_{new}, M_{air}, E_{eq}, \) and \( \beta_{ac} \) are unknown.

B. Identify Load Signature by Linear Regression

1) Linear Regression Model: By substituting (1) and (4) into (2), we construct a linear regression model to estimate the unknown parameters:

\[ \begin{bmatrix} n(t)(T_p - T_N(t)) \\ T_0(t) - T(t) \\ V_{cool}(T_{in}^w(t) - T_{out}^w(t)) \end{bmatrix}^T \begin{bmatrix} c_p \\ \alpha \\ -\beta_{ac} \end{bmatrix} = c M_z \Delta(t) \]  

(5)

where \( \alpha = c_{E_v} \beta_v + \frac{1}{R_{eq}} \) is the coefficients of \( T_0(t) - T(t) \) in the load model, which is treated as one unknown coefficient. We can rewrite (5) 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 \( \mathbf{A}_{1:t} = [\mathbf{A}(1), \mathbf{A}(2), \ldots, \mathbf{A}(t)]^T \), and an observation vector \( \mathbf{B}_{1:t} = [\mathbf{B}(1), \mathbf{B}(2), \ldots, \mathbf{B}(t)]^T \).

Then the problem of identifying the load signature is to identify the vector \( \theta \) by solving \( \mathbf{A}_{1:t} \theta = \mathbf{B}_{1:t} \), with the constraints that \( c_p, \alpha, \beta_{ac} \) are nonnegative.

Data collected from \( S_1 \) from a timespan of Aug 21th, 2013 to Aug 23th, 2013 was selected to solve the linear regression model. The dataset provides real-time \( T(t), T_{ac}(t), T_{in}^w(t), T_{out}^w(t), V_{cool}, \) 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. Based on these data, the observation matrix \( \mathbf{A}_{1:t} \) is constructed and the vector \( \mathbf{B}_{1:t} \) are constructed.

2) Solve the Linear Regression by a Search Algorithm:

Since the coefficients are required to be nonnegative, directly applying the least square estimation is inefficient. We propose a search algorithm to solve this constrained optimization problem:

\[ \theta = \arg \min_{[c_p, \alpha, \beta_{ac}]} \sum_{i=1}^{t} \| \mathbf{A}_{i,1:t} c_p + \mathbf{A}_{i,2:t} \alpha - \mathbf{A}_{i,3:t} \beta_{ac} - \mathbf{B}_i \|_2 \]  

subject to: \( c_p > 0, \alpha > 0, \beta_{ac} \geq 0 \)

\( \mathbf{A}_{i,j} \) is the item in \( i \)th column and \( j \)th row of the matrix \( \mathbf{A}_{1:t} \). Note that we divide the difference of the accumulated load vector and the accumulated supply vector by the accumulated load vector, which is to find the coefficient vector that can provide the minimum relative difference between the load and the supply vector. The search algorithm searches all combinations of \( [c_p, \alpha] \) for \( c_p < 1000 \) and \( \alpha < 10000 \). The parameter set \( [c_p^*, \alpha^*, -\beta_{ac}^*] \) which provides the overall minimum relative error is chosen as the optimal solution of problem (6). For the number of coefficients is limited, the computing complexity of the algorithm is tolerable.

3) Load Signatures of Subway HVAC: For the particular dataset of August 23, 2013 of \( S_1 \)[20], we calculated the optimal parameter set \( \theta \) as \( [83, 53703, -1290071]^T \). When varying the scope of the data, we found the solution vary within tolerable range of errors. By substituting the calculated coefficients into the load model, the derived load signature was plotted in Fig.7a). The real-time supplies calculated by the supply model are plotted in Fig.7b). We can see the supply flow closely to the load. The relative error between the integrated load and integrated supply is plotted in Fig.7c), 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 of a day is predictable according to the variations of 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.

C. Learned Insights for Energy Saving

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

1) The cooling part including refrigerators and pumps dominate the energy consumption of the HVAC.

2) To avoid the mismatch of load and supply, because in current (time-table based) control strategy, the indoor temperature is sometimes lower than the desired value
due to the higher supply than the load, and sometime higher due to the quickly increasing of the load. An energy efficient control strategy must be adaptive to the real-time load.

3) The conventional HVAC control strategy is not taking the variations characters of the passenger flow into consideration.

4) 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.

5) The pumps are over used. Each refrigerator is designed to work with one chilling pump and one cooling pump. But in the field study, we found that the number of running pumps are general larger than the designed number. The reason was found that the valves of the refrigerator pipes were not jointly controlled with the refrigerator.

V. 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 S1 station as an example.

A. Design Principles

The principle of our 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;

B. System Architecture

The architecture of our developed autonomous HVAC control system is shown in Fig.8. 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 Section III-D2, we deployed temperature, humidity, CO2 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. Frequency
Adapters 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.

C. Autonomous Control Policies for Energy Saving

Based on the hardware architecture, we designed autonomous control policies for controlling the HVAC system. For considerations of many practical issues, we designed and developed rule-based, adaptive control policies. These rule-based policies for different HVAC subsystems are summarized in Table III. Since the policies are depicted in detail in the table, we only explain some key points here:

1) The air enthalpy value [9] measured the amount of heat in a unit volume of air, whose formula is:

\[ i = 1.01 t + (2500 + 1.84 t) * 0.001d \]  

(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 [5] 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 adaptive to the load variations. Note that the policies in Table III are the result after many online test and evaluations. Although a predictive control strategy is possible based on the predictable load signature of the HVAC system, accurate load prediction is actually difficult because it needs much more information such as the weather, social events knowledge, and more powerful information fusion strategies. At current stage, we present the rule-based, adaptive strategy, which is reliable, needs much less information, and is practical.

VI. Implementation of Autonomous Control System

From April 2013 to July 2013, 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 the original control system can work normally in every morning after our development at the night, therefore, the autonomous control system was designed to coexist with the original control system. The control strategy and can be easily switched between each other.
A. Hardware System

The HVAC appliances used in the subway stations are from Carrier http://www.carrier.com.cn. We developed the central controller and the distributed controllers as introduced in Section V-B and deployed Profibus DP network to connect these control cabinets to the HVAC appliances. The figures of the central controller and the distributed controller are shown in Fig.9. 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. We deployed sensors as introduced in Section V-B. For a specific station $S_1$, the locations of the deployed sensors and a snapshot of their readings are shown in Fig.10. Note that the result is from our software interface.

B. 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. Actually, the control policy in Table III was the result after many times of modifications according to the real system performances.

Fig.10 shows a snapshot of the overview of the environment states rendered in the software interface. Fig.11 shows the water system state of the HVAC system, including the real-time temperatures of cooling water, chilling water, the working frequencies of the pumps, the states of valves, the load of the refrigerators and the states of the cooling tower. Fig.12 shows the wind system states in the HVAC system, including the temperature of the supply air and the returned air, the running states (including the real-time frequency, power, current and states etc.) of the supply fans, the exhaust fans and the new air fans. Alarming, parameter setting, energy saving report and control policy adjustment are also supported in the software interface.

VII. Running Result and 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.

A. Control Performance

The goal of the HVAC is to keep the indoor temperature and humidity varying within desired intervals during a day, called comfort intervals, to assure people feel comfort in the subway station.

1) Comfort Interval: Because passengers stay only short time in the subway station, the comfort interval in the subway stations is generally looser than that in home or in commercial buildings. The interval between 25$^\circ$C to 29$^\circ$C is set as the comfort temperature interval and 40% – 60% is set as the comfort humidity interval. Fig.13 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 5:00AM and 11:00PM are well control in the comfort interval. Fig.14 shows the humidity variations of the same day in the same station, in which the three curves show the readings of humidity sensors, which shows that the indoor humidity was also well controlled to be within the comfort interval.

2) Temperature peaks: The temperature variations in Fig.13 show that when the HVAC system was stopped at night the indoor temperature increased quickly. There were slightly temperature peaks at 8:00 AM because when the heating load increased quickly at the rushing hours, the indoor temperature increased before the HVAC system could take sufficient responses. Anyhow, the overall performances for temperature
and humidity control are satisfactory.

![Fig. 13. Temperature variations during a day on August 23, 2013](image1)

![Fig. 14. Humidity variations during a day in August 23, 2013](image2)

![Fig. 15. How the indoor temperature response to the cooling supply of the HVAC system](image3)

3) **Respond speed:** We also evaluated how the indoor temperature was affected by the cooling supply of the HVAC system. We measured the cooling supply of the HVAC system by the temperature of the cooling air blown by the cooling fans. Fig.15 shows the variation of the indoor temperature in a subway station over a day following the temperature variations of the cooling air. We can see that when the temperature of the cooling air changed, the indoor temperature changed quickly, which shows that the indoor temperature has short responding time to the cooling supply of the HVAC.

4) **Adaptivity of the Refrigerators:** We further investigated how the working states and energy consumptions of the refrigerators change over a day with the variations of the outdoor temperatures. Fig.16a) shows the temperature variations and indoor-outdoor temperature differences over a day. Fig.16b) shows the concurrent working states and the energy consumptions of the two refrigerators in that day. We can see the working loads of the refrigerators are closely and fast responding to the indoor-outdoor temperature differences.

**B. Energy Saving Performance**

We evaluated the energy saving performances of the autonomous control system 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 energy consumptions of the HVAC systems in each day in the three subway stations are listed in column 2 to 4 in Table IV. The three days in which we ran the conventional control policy were highlighted.

1) **Energy consumption is dependent on the outdoor temperature:** At first, we can see that the energy consumptions of the HVAC system in a day were highly dependent on the average outdoor temperature of the day. The fifth column of the table shows the average outdoor temperature from 8:00AM to 10:00PM in 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, which coincides our common sense.

**TABLE IV**

<table>
<thead>
<tr>
<th>Time</th>
<th>$S_1$</th>
<th>$S_2$</th>
<th>$S_3$</th>
<th>$T_a(t)$</th>
<th>$T(t)$</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>4644.294</td>
<td>5928.829</td>
<td>7922.496</td>
<td>28.38</td>
<td>29.19</td>
<td>auto</td>
</tr>
<tr>
<td>8</td>
<td>6859.793</td>
<td>5850.69</td>
<td>10123.82</td>
<td>31.52</td>
<td>29.21</td>
<td>auto</td>
</tr>
<tr>
<td>9</td>
<td>5757.094</td>
<td>9897.5</td>
<td>13580.29</td>
<td>33.03</td>
<td>29.56</td>
<td>auto</td>
</tr>
<tr>
<td>10</td>
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<td>6777.309</td>
<td>6484</td>
<td>33.85</td>
<td>29.84</td>
<td>auto</td>
</tr>
<tr>
<td>11</td>
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<td>7475.777</td>
<td>6772.504</td>
<td>31</td>
<td>29.6</td>
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<td>12</td>
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<td>7083.711</td>
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<td>30</td>
<td>29.3</td>
<td>auto</td>
</tr>
<tr>
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<td>10554.38</td>
<td>12782.09</td>
<td>31.24</td>
<td>27.99</td>
<td>old</td>
</tr>
<tr>
<td>14</td>
<td>5603.398</td>
<td>6987.33</td>
<td>7411.109</td>
<td>31.52</td>
<td>28.15</td>
<td>auto</td>
</tr>
<tr>
<td>15</td>
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<td>6504.684</td>
<td>8130.896</td>
<td>33.53</td>
<td>30.15</td>
<td>auto</td>
</tr>
<tr>
<td>16</td>
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<td>5518.301</td>
<td>6252.008</td>
<td>30.96</td>
<td>30.32</td>
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<tr>
<td>17</td>
<td>7639.799</td>
<td>7715.895</td>
<td>10464.5</td>
<td>36.32</td>
<td>28.74</td>
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</tr>
<tr>
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<td>7569.996</td>
<td>7126.309</td>
<td>6636.703</td>
<td>33.07</td>
<td>28.74</td>
<td>auto</td>
</tr>
<tr>
<td>19</td>
<td>7142.816</td>
<td>7265.707</td>
<td>7462.195</td>
<td>32.63</td>
<td>28.48</td>
<td>auto</td>
</tr>
<tr>
<td>20</td>
<td>4869.703</td>
<td>5487.184</td>
<td>7927.684</td>
<td>29.99</td>
<td>28.79</td>
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</tr>
<tr>
<td>21</td>
<td>5794.017</td>
<td>5608.193</td>
<td>6580.805</td>
<td>29.48</td>
<td>28.86</td>
<td>auto</td>
</tr>
<tr>
<td>22</td>
<td>10313.89</td>
<td>7381.176</td>
<td>8992.219</td>
<td>29.45</td>
<td>27.59</td>
<td>old</td>
</tr>
<tr>
<td>23</td>
<td>5058.072</td>
<td>4115.918</td>
<td>4803.492</td>
<td>32.07</td>
<td>28.45</td>
<td>auto</td>
</tr>
<tr>
<td>24</td>
<td>5598.16</td>
<td>4966.538</td>
<td>4825.138</td>
<td>29.95</td>
<td>28.5</td>
<td>auto</td>
</tr>
</tbody>
</table>

2) **Energy saving performance:** Since the energy consumption of the HVAC system was positively correlated to the average outdoor temperature, we select the days that had similar outdoor temperatures to compare the energy consumptions of the conventional and autonomous running modes. So that 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 V. From the results, it can be seen that, for example,
in $S_1$, the autonomous control system can save more than 2000Kwh power per day. The average energy saving ratio in $S_1$ is over 38%, in $S_2$ is over 19% and in $S_3$ is over %32.

3) Economic benefit: Since the HVAC system works for more than 100 days in a summer, if 2000Kwh energy is saved per day, more than 200,000 Kwh power can be saved in a summer, in one subway station. Therefore, the autonomous control system can not only reduce the energy consumption of the subway to make the subway be more environment friendly, but also can bring tangible economic benefit to the operating company via reducing the operating cost.

VIII. 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 consumptions of the HVAC, the refrigerators and the pumps take the greatest portion. Further, by investigating the loads of HVAC systems in the subways, we show the heating load has predictable signatures, according to the variation of outdoor temperature and the passenger flows. The outdoor temperature’s impact generally is more significant than the passenger flow. These investigations show the conventional time-table based control strategy lacks adaptivity and may trigger load-supply mismatch. To tackles these problems, we presented autonomous control system by deploying sensors, distributed control unites, electrical valves and frequency adapters into the HVAC system. We carefully designed the rule-based control policies by online tests and evaluations. The new control policies improve the adaptivity of the HVAC system and as the result save energy for 20% to 38% in different stations.

In future work, if more information about the weather, the social events, and the system states can be available in real-time, the prediction of the outdoor environment and the passenger flow can be more accurate, which may enable prediction-based HVAC control strategy. Efficient information collection and more accurate system state estimation is also an important research direction, which can provide fine-grained insights about the energy waste in HVAC. Cost efficient, effective, autonomous control devices and standards are still need to be explored.

TABLE V
ENERGY SAVING PERFORMANCE OF AUTONOMOUS CONTROL

<table>
<thead>
<tr>
<th>Station Names</th>
<th>$S_1$</th>
<th>$S_2$</th>
<th>$S_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>average of Aug. 8, 13 in old mode</td>
<td>6766.84</td>
<td>8202.71</td>
<td>11497.95</td>
</tr>
<tr>
<td>average of Aug. 11, 14 in auto mode</td>
<td>4700.5</td>
<td>7231.8</td>
<td>7257.3</td>
</tr>
<tr>
<td>Saved Energy</td>
<td>2066.34</td>
<td>970.9</td>
<td>4240.64</td>
</tr>
<tr>
<td>Energy saving ratio</td>
<td>0.305</td>
<td>0.118</td>
<td>0.274</td>
</tr>
<tr>
<td>average of Aug. 22 in old mode</td>
<td>10313.89</td>
<td>7381.17</td>
<td>8992.21</td>
</tr>
<tr>
<td>average of Aug. 20,21,24, auto</td>
<td>5420.62</td>
<td>5353.97</td>
<td>6444.54</td>
</tr>
<tr>
<td>Saved Energy</td>
<td>4893.26</td>
<td>2027.20</td>
<td>2547.67</td>
</tr>
<tr>
<td>Energy saving ratio</td>
<td>0.474</td>
<td>0.274</td>
<td>0.283</td>
</tr>
<tr>
<td>Average energy saving ratio</td>
<td>0.389</td>
<td>0.196</td>
<td>0.326</td>
</tr>
</tbody>
</table>

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