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The status quo of operation of HVAC water-side systems in China: a perspective from BAS data

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Abstract

Building stock is a substantial consumer of energy worldwide, and HVAC systems are substantial consumers in buildings. Therefore, it is of great importance to improve the energy efficiency of HVAC systems. For existing HVAC systems, energy savings can be achieved by optimizing the operation strategies. To identify current chiller operation limitations, and evaluate their impacts on energy consumption, a systematic study has been performed. First, the information about operation strategies in about 15 buildings are collected, by either on-site survey or data mining from BAS data. Then, three features(i.e. Avg_p , Std_p and R_{cap_T}) are proposed to characterize these operation strategies. Finally, the influence of these three features on cooling energy consumptions are analyzed. It is found that R_{cap_T} (correlation coefficient between cooling capacity of online chillers and outdoor air temperature) has strong negative impact on cooling energy usage.

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Keywords: operations; water-side HVAC systems; read measured data;

1. Introduction

Building stock is a substantial consumer of energy worldwide, and the contribution from building stock towards energy consumption, both residential and commercial, is approximately equal to or greater than the other major sectors: industrial and transportation. According to the data from EIA [1], compared to industrial sector and transportation sector, in 2017 the total energy consumption by building stock is 23% and 34% greater, respectively.

HVAC systems are substantial consumers in buildings. And besides their designs, the operation of HVAC

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systems significantly determines their energy efficiency or cost-effectiveness. Optimal control of HVAC systems formulates the operation of an HVAC system as an optimization problem and then computes a control solution that minimizes a certain cost function in the presence of disturbance and constraints. And the research on optimal control has a history longer than 30 years [2], and up to now thousands of papers on this topic are published. Pleasing as this may sound, optimal control methods are not widely applied to HVAC systems. And the first priority of HVAC community is to investigate the status quo of operation of HVAC systems. This paper, therefore, exploring the current situation of operation of water-side systems in commercial building in Shanghai, China, hoping this study will reflect the situation of whole HVAC systems on a larger spatial scale to some extent. This paper achieve this target through answering these questions:

1) What proportion of HVAC systems is equipped with optimal controllers?
2) Do the control strategies vary with characteristics of buildings (e.g. age, function or location of buildings)?
3) To what extent is energy consumption influenced by control strategies?

2. Methodology

The dataset of operation information of HVAC systems is collected in two ways: on-site interviewing with operation staff, and mining from BAS (building automation system) data.

2.1. On-site interview

On-site interviews with operation staff is a direct way to collect information. However, it is a highly time-consuming process. Therefore, only *three* large public buildings were selected to conduct interviews, and the obtained data are mainly used as data basis for validating our data mining method.

The interview questions are mainly involved with the general information about chiller plants, operation strategies and thermal performance of the system. The obtained results will be presented in the following section.

2.2. BAS data mining

Data mining can automatically extract information from a data set and transform it into useful knowledge for further use. In our case, knowledge are the actual operation strategies applied in water-side systems, and the database used to feed data mining algorithms are BAS data.

The operation strategies of water-side systems mainly refer to the setpoints of chilled water supply temperature and sequencing control of chillers. The identification algorithm used in this paper was published in a previous paper by the authors [3]. To keep this paper self-contained of this paper, the algorithm will be outlined briefly.

The decision structures underlying the operations of water-side systems (even most building systems) can be visualized as decision trees, as shown in Figure 1. This decision tree is featured by two characteristics: 1) each variable could be tested only once on any path from the root (the top first node) to the leaf (the bottom nodes). That is, once you have branched on a attribute, this variable will not be used in any path derived from this node. 2)The tree is multi-way, where each internal node branches to two or more other nodes. To extract such a decision tree from BAS data, we developed a multi-way decision tree algorithm. Compared with the two classic decision tree induction algorithms--C4.5 and CART, this multi-way decision tree induction algorithm applies multi-way splits to both nominal and continuous variables, and each variables will be tested only once. Therefore, our multi-way decision tree induction algorithm is naturally suitable for mining the operations of water-side systems. For more detail about this algorithm, please refer to paper [3].

3. Result

3.1. Result of on-site interview

Through interview with the operation staff in these three selected buildings, it is found that none of these HVAC systems is equipped with optimal controllers, and the setpoints and operation modes of the HVAC systems are fully decided by the operation experts. Besides, none of the operation logbooks of these buildings records each operation change occurring to the systems, and the records available can only specify the cooling periods in a year, which are also full of ambiguities. Fig. 1 presents the decision process for cooling requirement of one surveyed building, where "On" or "Off" means the cooling systems are turned on or off, respectively.

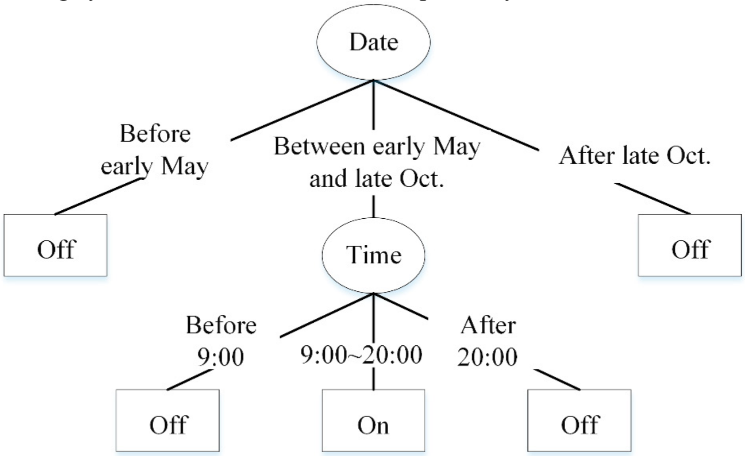

Fig. 1. Decision process for cooling requirement of a building in Shanghai

Setpoints of supply chilled water temperature are held constant, and sequencing control strategies in these systems are all scheduled beforehand, which means that the order and conditions associated with bringing chillers online or moving them offline are pre-defined by the operation experts only considering date and time.

This kind of scheduled operation can be featured by the following characteristics:

1) The operation modes of chillers are defined by operation staff according to their thermal sensation, therefore the correlation between cooling capacities and actual cooling load is not very significant.
2) Most operation staff tend to keep an operation mode for a long period, say one week. These two features will be further confirmed from the result of BAS data mining.

3.2. Result of BAS data mining

The database for our study consists of about 30 large public buildings, among which most are office buildings and shopping malls. This collection only includes detailed power meter data. Hence, the analysis of decision pattern for setpoints of chilled water supply temperature could not be conducted in this paper. And we focus on the chiller sequencing control strategies. This database can provide chiller electricity consumption, where were taken at 15 min intervals.

The chiller electricity consumptions are used as target variables in our MDT methods, and the input variables include: dayOfYear (range: 1~365), month(range:1~12), day(range:1~12), hour(range:0~23), weekendOrHoliday(range: {yes, no}), and Tout(range: [0~inf], unit: K).

Fig.2 shows the identified chiller sequencing control of aforementioned building-DMTGC, whose chiller plant consists of two identical chillers. The leaf nodes in this tree consists of two parts: the number in the upper part represents the number of online chillers for a leaf, and the fraction in the lower part represents the misclassification rate for this leaf. Taking the first leaf node in the first level as an example, 1/2904 means there is one observations in this set whose target variable does not take 0.

From this obtained tree, it is clear that only two variables (i.e. dayOfYear and Hour) are used as splitting variables. This further confirms that the operation of chiller plant in this building are decided by operation staff only with regard to date and time, and there is no strong relation between cooling load and the number of online chillers. From Fig.2, the cooling period spans from the 122rd day of this year (2rd May) to the 298rd day (25th Oct), which are consistent with the record in the logbook: from early May to late Oct. In addition, the whole cooling season is divided into three periods, and the operation modes are held constant during each period. 1 for period 1 (from 2rd May to 25th Jul.) and period 3(from 12th Aug. to 25th Oct) and 2 for period 2(from 26th Jul. to 11th Aug.) This suggests that the operation strategy in this building is highly scheduled, and the switch frequency of chiller plant are very low. Compared to optimal on-demand operation, this scheduled operation is certainly less energy-efficiency.

Then this automated data mining algorithm is applied to each building in the database. Surprisingly, all the sequencing controls of chiller plants in these building are scheduled operation. In the future, the reasons underlying this phenomenon and the implementation issues of optimal control strategies should be addressed in order to putting existing research into application.

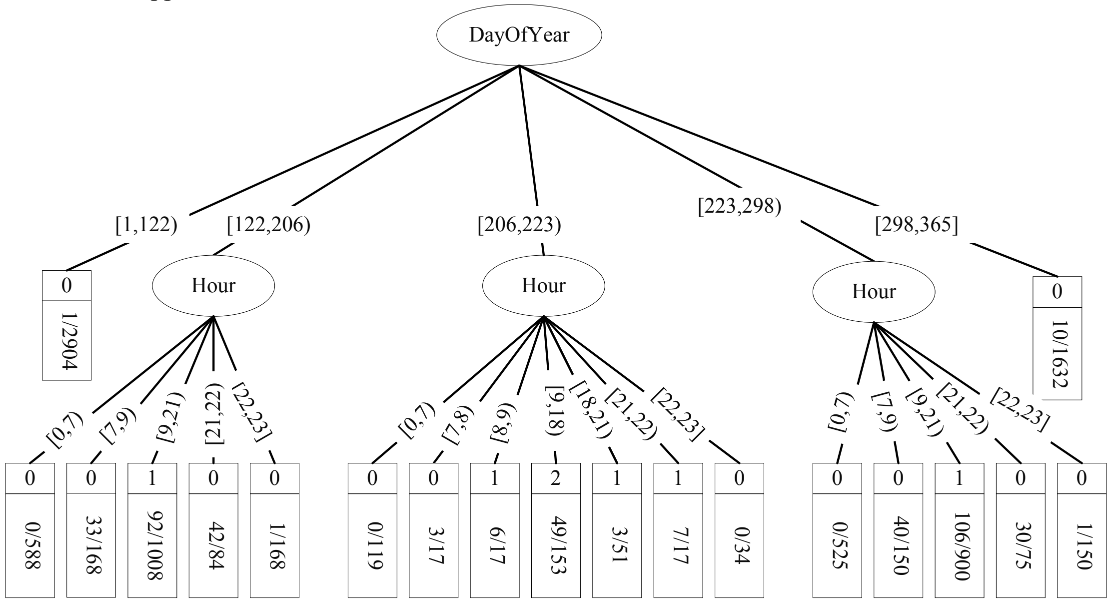

Fig.2. Decision tree for chiller sequencing control of DMTGC

1) quantification methods of the scheduled operations

In order to answer whether the scheduled operation patterns will vary with characteristics of buildings (e.g. age, function or location of buildings), we need to define several features to characterize the scheduled operations. Herein, we proposed three features: the average length of all operation periods in days, Avg_p , the standard variance of all lengths Std_p , and correlation coefficient between cooling capacity of online chillers and outdoor air temperature R_{cap_T} . Taking the result of DMTGC as example, there are three periods, and the lengths are 84, 17, and 75 days. Thus, Avg_p is 58.67, Std_p is 36.36. The correlation coefficient used in this paper is Pearson's correlation coefficient [4], which is defined as Eq. (1)

$$R_{cap\_T} = \frac{\sum (Cap_i - \overline{Cap})(T_i - \overline{T})}{\sqrt{\sum (Cap_i - \overline{Cap})^2 \sum (T_i - \overline{T})^2}} \tag{1}$$

where Cap_i is the cooling capacity of all online chillers at time i , T_i is the outdoor air temperature at time i .

2) Feature representation

Then, we calculated the three features of the operation for each building, and the result are shown in Fig.3. From this figure, it can be observed that Avg_p of each building ranges from about one week to one month, with only one exception at the value of 180. This suggests that the switch frequency of chiller plants in these buildings are all very low, which are obviously not on-demand optimal controls because high fluctuations of cooling loads will lead to high switch frequency. Second, these operations are quite similar since there is not significant variation in terms of both Avg_p and Std_p, and the function of buildings do not have strong influence on the control strategy. Last, the R_{cap_T} of all these buildings are almost at the same level, this further confirms that these systems are not equipped with optimal controllers.

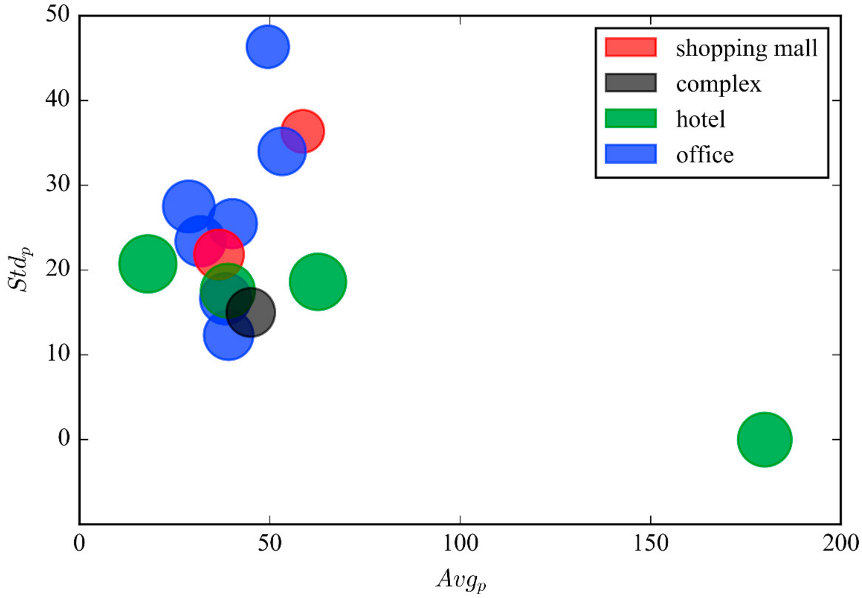

Fig.3 features of the operations of the investigated buildings (Note: the sizes of bubbles are R_{cap_T} for each sample)

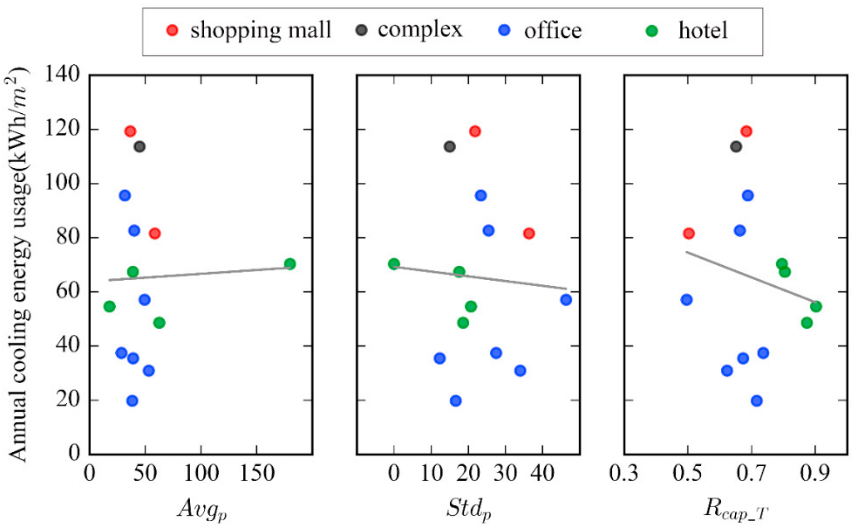

Fig. 4. Scatter plots of annual cooling energy usage and Avg_p (left), Std_p (mid) and R_{cap_T} (right)

3) Influence of operation on electricity usage

Fig.4 shows the correlation between these operation features and annual cooling electricity usage(per unit area). Among these four features, R_{cap_T} has significant relation with electricity usages, and this is true whether the function of building are isolated or not. Since outdoor air temperature is strongly related to cooling load, R_{cap_T} grows, then the shape of the curve of cooling capacity of all online chillers is more similar to the shape of the curve of cooling load, which means less electricity are wasted when cooling load are relatively low. It should be noted that this conclusion is based on the assumption that the thermal performance of all these HVAC systems are almost the same. Besides, the impacts of other two variables(i.e. Avg_p and Std_p) are not so apparent. Last, since there are only 14 samples, these relationships should be further explored.

4. Conclusion

In this paper, we have explored the current situation of operations of HVAC water-side systems in Shanghai, China. The information used for analysis are collected from on-site surveys and data mining from BAS data. It is found that no one of these surveyed buildings adopts optimal on-demand control. On the contrary, chiller plants of all these buildings are manually controlled by operation staff. Then, when it comes to the influence of operation strategy on electricity usage, it is found that the operation strategy with lower R_{cap_T} is more energy-efficient. All

these results point out that there is a long way to go for building HVAC scientists and professionals to make optimal control strategies fully utilized in practice.

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