Building Automation System Alarm Management for Operation and Maintenance Decision Making

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ABSTRACT

Building systems, including Heating, Ventilation and Air-conditioning (HVAC) systems, lighting systems, and security systems are key components of modern buildings. These systems are designed to deliver an ideal built environment, ensure the quality of building service and safety. The implementation of Building Automation System (BAS) has facilitated the building Operation and Maintenance (O&M), allowing building operators to better monitor and regulate building functions. One of the important abilities of modern BAS is raising alarms when building systems behave differently from design values. However, BAS usually generates an excessive amount of alarms every day. The lack of actionable information from those alarms makes it very challenging for building operators to take actions. The intent of this study is to find the reasons of the inefficiency of BAS alarm functions and to propose a solution which helps building operators make better O&M decisions based on the BAS alarms. This study analyzed a BAS in a university complex. First, the building's HVAC systems were investigated. Second, interviews with facility managers and BAS field engineers were conducted to identify the existing deficiencies of BAS and future user expectations. Third, a data-mining framework was constructed to optimize current BAS alarm management function. The goal of this framework is to help filter out trivial alarms, categorize alarms by their impact category (e.g. equipment-related, occupant-related, critical equipment operations), and prioritize the alarms based on the quantitative impacts. This paper presents an alarm management optimization solution for an 111754 sqft-complex on Carnegie Mellon University campus in Pittsburgh, PA. This study found that a good BAS alarm management function should be a collaborative effort among designers, BAS engineers, and building operators. Current deficiencies of BAS alarm management are caused by poor rule definitions and information isolations. The framework from this study could effectively filter out the trivial alarms from BAS, and provide actionable information for building operators.

INTRODUCTION

Commercial buildings account for 19% of the total energy consumption in the United States. More than 50% of the energy consumed by commercial buildings goes toward space heating, ventilation and air-conditioning system and lighting system (ACEEE 2016). Building Automation System (BAS) has become increasingly popular under such a circumstance. A BAS is a distributed control system that helps to monitor and regulate building systems. When being properly applied, BAS can help to save considerable energy (Ahmed, Korres, Ploennigs, Elhadi, & Menzel, 2010). Commercial buildings implementing BAS are estimated to save an average 10% of overall energy consumption (Sustar and Goldschmidt 2007). In addition to energy savings, BAS can also help facility managers to maintain comfort levels in occupant spaces, and raise alarms when abnormal situations happen in building systems.

However, BAS's abilities such as system monitoring and controlling are often underutilized by various operational challenges (Munasinghe 2016). One of the challenges is the overwhelming amount of alarms generated by

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BAS every day. Most of the alarms have no self-diagnostics for possible reasons and potential impacts, and provide no actionable information. Thus, it becomes very difficult for facility managers to make preventive O&M decisions. For example, one of the six BAS solutions on CMU's Pittsburgh campus has generated over 610,000 alarms during the year of 2010 and 2016. One of the most frequent types of alarms is 'Zone temperature abnormal' and 'Zone temperature normal'. An investigation shows that this type of alarms is caused by poor rule definition. The BAS continuously generates those alarms when the temperature in a zone fluctuates around the alarm thresholds. However, those alarms do not equal to 'faults' in HVAC systems. So, the facility managers choose to acknowledge them without any further inspection and maintenance, if not just ignore them. This could end up with energy waste, poor comfort level and even wrongly ignoring of severe alarms.

Meanwhile, control systems for industrial processes are being continuously developed. Recent studies in the field of automation have shown that alarm management system along with sensing technologies can provide a good support for decision making and management. An analysis of alarm logs in the field of marine technology was conducted to identify and analyze abnormal situations that could affect process safety (Urban & Landryová, 2016). The alarm packages they used in the study are log files from a vessel control system. Their study supports the development of an engineering tool which allows operators to decide which alarms need immediate attention and which alarms could be postponed. To our knowledge, there is no similar study in building control field that addresses alarm filtering and ranking issues.

Therefore, this paper aims to study BAS's alarm management functions in supporting building system O&M. Specifically, section 2 discusses the key findings from the interview with building operators regarding current issues with the BAS alarm management function and future expectations. Section 3 proposes a data-mining framework to process raw alarm data from a BAS, and classify and prioritize the alarms. Section 4 demonstrates an implementation of the framework in a case study on CMU campus. Section 5 summarizes the key findings, conclusions, and future work.

INTERVIEW WITH BUILDING OPERATORS

The goal of this paper is to optimize the alarm management function for facility managers so that they can make informed operation and maintenance decisions. Thus, it is necessary to understand the pros and cons of the current alarm management tool, and the user needs for future tools. A set of interviews is conducted to collect the opinions of building operators including facility managers and BAS field engineers. This section summarizes the current issues and future expectations for BAS's alarm management function.

Current Issues

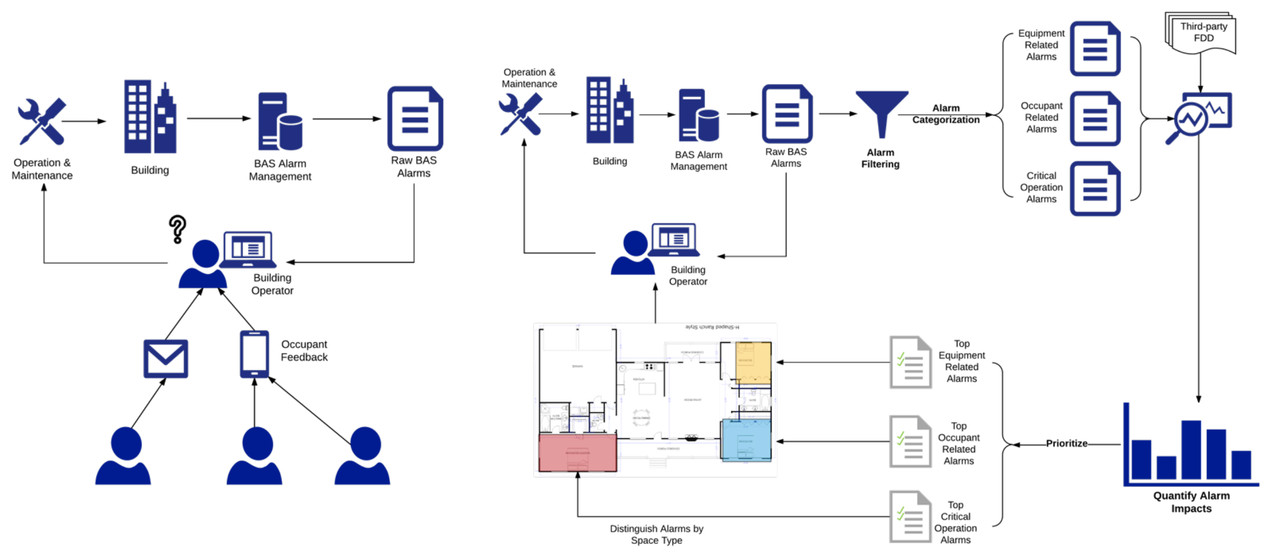
From the interview, it was found that facility managers do not rely a lot on the alarm management function provided by BAS solutions. There are several reasons. Firstly, there are too many alarms. It's impossible for facility managers to be notified (usually by text message or email) when every single alarm occurs. Secondly, the information provided by the alarms is very limited. An alarm only provides the name of a device and some high-level descriptions. But no potential impacts and possible reasons are provided. Thirdly, most of the alarms are trivial and are not directly associated with faults in HVAC systems. Originally, alarms are designed to guide facility managers. But they are only considered as an insignificant reference in the real world. In most cases, facility managers make operational decisions based on their own experience. There is an obvious gap between what the user needs for BAS alarm management and what the tools provide. Because of the lack of actionable information provided by the alarms, facility management is likely to be reactive instead of proactive. A BAS is a big investment for an organization. The cost of deploying a basic BAS can be up to $7/sqft (Rawal 2016). Thus, it is wasteful if the tool does not contribute to building systems' operation at its full potential.

Expectations

From the interview, the needs for future alarm management tools can be summarized as: simple, accurate, and powerful. The future alarm management tools in BAS should be more user-friendly. It should provide very clear information about the alarm and avoid meaningless and lengthy descriptions. It should be accurate—the trivial alarms should appear on the dashboard. It should help building operators make better operational decisions. For example, it can embed FDD algorithms and show the root cause of the alarms, and display the alarm and faults on the floorplan. It can also provide suggestions of how to react to the alarms and what the potential impacts are. This paper is to improve the alarm management function of BAS by classifying and prioritizing alarms.

DATA-MINING FRAMEWORK

Traditionally, BAS alarms are transmitted to building operators without sufficient actionable information. As shown in Figure 1 a), when alarms are generated, they are simply stored in alarm logs. Without proper classification and prioritization, potentially important alarms are often disguised by trivial ones. Building operators can not take advantage of the BAS alarm management function. To solve this problem, this paper proposes a data-mining framework that helps classify and prioritize BAS alarms. As shown in Figure 1 b), raw alarms are firstly classified based on their impact categories (i.e. equipment, occupant, critical operations). Then, the potential impacts of the alarms could be quantified. Finally, top alarms with detailed information including building, floor, space, related equipment, and durations could be shown to building operator. With this framework, top alarms from different categories could be shown based on user preferences, which could help building operators make informed O&M decisions. The main steps in the framework are discussed in this section.



a) b)

Figure 1 (a) Current alarm management schema and (b) proposed data-mining framework for alarm management.

The proposed data-mining framework includes the following parts: (1) Raw alarm collection. The plain text format raw alarm data is collected from BAS. Each entry represents an alarm which has some descriptive features. The alarms from the target buildings are extracted for next steps. (2) Data preprocessing. The raw data has only several descriptive features, which is not interpretable for manual alarm analysis and not readable for data-mining algorithms. In this step, alarm data is parsed in a tabular format. (3) Categorizing BAS alarms. After the alarms are preprocessed, they can be categorized into several categories (e.g., equipment related, occupant related, critical operation related). (4) Prioritizing BAS alarms. The impacts of certain alarms are evaluated based on the findings from literature reviews and first principle calculations. With the quantified impacts and durations, the alarms can be ranked per user preferences. (5) Feedback to facility managers. Based on user preferences, the alarms with top impacts are shown to facility managers along with actionable information (e.g., measures to acknowledge the alarm, control sequences, root cause of the alarms, and maintenance recommendation.)

A CASE STUDY

The data-mining framework is implemented on the BAS alarms from a complex building on CMU campus. The raw alarm contains over 84,000 alarms during Feb 2010 to Feb 2016. In this section, data collection and preprocessing, alarm categorization, alarm impact quantification, and duration prediction are discussed. The case study demonstrates how the raw alarms are processed into a machine-readable format, how they are categorized into equipment-related, occupant-related, and critical operation alarms. It then shows how occupant-related alarms could be prioritized based on their potential energy consumption and thermal comfort impacts.

Data Preprocessing

Data preprocessing is the prerequisite for data-mining. In this case, the original alarms are stored in a text file with lengthy descriptions and random characters. Therefore, it's necessary to convert the raw alarms from text format to tabular format that can be analyzed by data-mining algorithms. Ten original column features are extracted for each alarm. Table 1 shows the names of the original features and their meaning.

Table 1. Original Features Names and Meaning

Number	Feature name	Meaning
1	status	The alarm status, "off normal", and "normal"
2	building	The building where the alarm occurs
3	floor	The floor where the alarm occurs
4	system	The system where the alarm occurs
5	short_info	Short name of the alarm from the BAS dashboard
6	range	The range of the alarm
7	description	Long description of the alarm
8	fms	The facility manager who acknowledged the alarm
9	occur	The time when an alarm occurred
10	acknowledge	The time when an alarm was acknowledged

Although the alarms are machine-readable after extracting the column features, those features don't provide enough useful information as they potentially could. Therefore, several steps of feature space reconfiguration are necessary.

Breakdown Temporal Features. The original "occur" and "acknowledge" features are in string format which doesn't provide any temporal information. It is necessary to break it down into different features. Figure 2 shows an example of how a temporal feature can be broken down into several features so that it can provide more meaningful information.

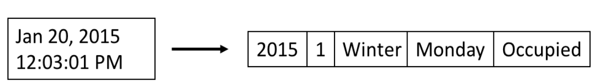
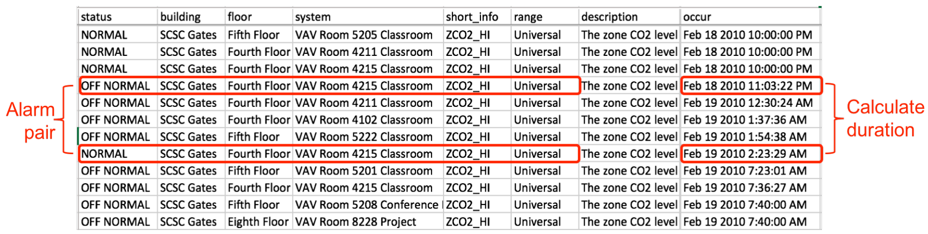


Figure 2 String format temporal feature is broken down into several features.

Calculate Alarm Durations. The "status" feature of an alarm has two possible values: "off normal" or "normal". The BAS raises an "off normal" alarm when the value of a certain parameter exceeds the threshold and last for a period. When the value returns to the normal range, the BAS raises another alarm with the status being "normal", indicating the alarm is released. The interval between those two alarms is the duration. Figure 3 shows how alarm durations are calculated.



status	building	floor	system	short_info	range	description	occur
NORMAL	SCSC Gates	Fifth Floor	VAV Room 5205 Classroom	ZCO2_HI	Universal	The zone CO2 level	Feb 18 2010 10:00:00 PM
NORMAL	SCSC Gates	Fourth Floor	VAV Room 4211 Classroom	ZCO2_HI	Universal	The zone CO2 level	Feb 18 2010 10:00:00 PM
NORMAL	SCSC Gates	Fourth Floor	VAV Room 4215 Classroom	ZCO2_HI	Universal	The zone CO2 level	Feb 18 2010 10:00:00 PM
OFF NORMAL	SCSC Gates	Fourth Floor	VAV Room 4215 Classroom	ZCO2_HI	Universal	The zone CO2 level	Feb 18 2010 11:03:22 PM
OFF NORMAL	SCSC Gates	Fourth Floor	VAV Room 4211 Classroom	ZCO2_HI	Universal	The zone CO2 level	Feb 19 2010 12:30:24 AM
OFF NORMAL	SCSC Gates	Fourth Floor	VAV Room 4102 Classroom	ZCO2_HI	Universal	The zone CO2 level	Feb 19 2010 1:37:36 AM
OFF NORMAL	SCSC Gates	Fifth Floor	VAV Room 5222 Classroom	ZCO2_HI	Universal	The zone CO2 level	Feb 19 2010 1:54:38 AM
NORMAL	SCSC Gates	Fourth Floor	VAV Room 4215 Classroom	ZCO2_HI	Universal	The zone CO2 level	Feb 19 2010 2:23:29 AM
OFF NORMAL	SCSC Gates	Fifth Floor	VAV Room 5201 Classroom	ZCO2_HI	Universal	The zone CO2 level	Feb 19 2010 7:23:01 AM
OFF NORMAL	SCSC Gates	Fourth Floor	VAV Room 4215 Classroom	ZCO2_HI	Universal	The zone CO2 level	Feb 19 2010 7:36:27 AM
OFF NORMAL	SCSC Gates	Fifth Floor	VAV Room 5208 Conference	ZCO2_HI	Universal	The zone CO2 level	Feb 19 2010 7:40:00 AM
OFF NORMAL	SCSC Gates	Eighth Floor	VAV Room 8228 Project	ZCO2_HI	Universal	The zone CO2 level	Feb 19 2010 7:40:00 AM

Figure 3 Calculate alarm duration.

Attach AHU Relations. The original alarms provide location information at the zone level. For instance, from the alarm building operators can see the floor and room number. However, those alarms don't provide any information related to the system. In this step, the rooms are mapped to AHUs. This way, building operators can see the potential patterns of the alarms.

Alarm Categorization

To investigate the patterns, the alarms are categorized based on their affected objects. They are firstly divided into different space type groups and then categorized into Occupant-related, Equipment-related, and Critical operation groups. Table 2 shows the categorization rules.

Table 2. Alarm Categorization by Affected Objects

Naming Convention of Alarms	Space Type	Category
VAV Room ####, VAV Room Office, Dean's Suite	Office	Occupant-related
Classroom, Project, Reading	Classroom	
VAV Room #### Conference, Future Use	Conference	
Café, Corridor, Bridge, Study Carrell, Lobby, Collaboration Space, Collaborative Common, Nursing	Common	
Kitchenette, Work/Copy/Print, Storage, Reception/Mail	Service	
AHU, FCU, CHW, HWS	HVAC Equipment	Equipment-related
Energy Meter, Monitoring, Sensor	Meters	
Emergency Generator, Garage Exhaust, Electrical Closet, CRAC, Chilled Water System, Hot Water System, Rainwater System	Critical	Critical Operation

Alarm Prioritization

To prioritize the alarms, the potential impacts need to be quantified. Energy consumption and thermal comfort are two key metrics to quantify the impacts of occupant-related alarms. This section presents the calculation of instantaneous and long-term impacts. The alarm prioritization based on those two metrics are then discussed.

Energy Consumption Impact. Due to the lack of energy metering and sub-metering in the sample building, there is no direct way of evaluating the energy impacts of the alarms. However, since most rooms in the building are served by VAV terminal units. And the discharge air temperature and airflow rate, room air temperature under alarm condition and normal condition can be acquired from the BAS. A first principle method is used to calculate the energy consumption rate impact under alarm conditions. The energy transfer rate (kW) between discharge air and room air can be calculated with Equation (1).

$$\dot{Q} = \dot{V}C_v(t_{discharge}\text{-}t_{room}) \tag{1}$$

Then, the difference of energy transfer rate between alarm condition and normal condition can be calculated with Equation (2), which is the energy consumption rate impact.

$$\Delta\dot{Q} = \dot{Q}_{alarm}\text{-}\dot{Q}_{normal} \tag{2}$$

With the energy transfer rate impact and alarm duration, the energy consumption impact (kWh) can be calculated with Equation (3).

$$Energy\ Impact = \Delta\dot{Q} \times Duration \tag{3}$$

Thermal Comfort Impact. Thermal comfort can be quantified with Predicted Mean Vote (PMV). According to Fanger's thermal comfort model (Fanger, P.O. 1989), PMV is a function of metabolic rate, clothing factor, air dry-bulb temperature, mean radiant temperature, relative humidity, and local air velocity. In this study, the PMV values under alarm conditions are calculated with the assumptions in Table 3.

Table 3. PMV Calculation Parameters

Mode	Cooling		Heating	
Space Type	Office, Classroom	Service, Common	Office, Classroom	Service, Common
Base Metabolic Rate (W)	58.15	58.15	58.15	58.15
Relative Metabolic Rate	1.1	1.2	1.1	1.2
Clothing Factor	0.5	0.5	1	1
Air Dry-bulb Temperature (˚C)	Assumed to be the zone air temperature.			
Mean Radiant Temperature (˚C)	Assumed to be the zone air temperature.			
Air Relative Humidity (%)	50%	50%	40%	40%

Like energy consumption impact, the cumulative thermal comfort impact can be calculated with Equation (4). To reflect both hot and cold situations, the absolute values of PMV is used in the calculation.

$$Thermal\ Comfort\ Impact = |PMV| \times Duration \tag{4}$$

Total Impact. After the energy consumption and thermal comfort impacts being quantified, the alarms can be prioritized based on their total impacts. Since the of energy consumption and thermal comfort have different priority in different space types, different levels of impacts could be assigned to them. For example, energy consumption has the same priority in different spaces, while office rooms may have higher thermal comfort priority than corridors because occupants spend the longer time in them. Figure 4 shows an example of energy consumption impact and thermal comfort impact normalization and grouping by different space type.

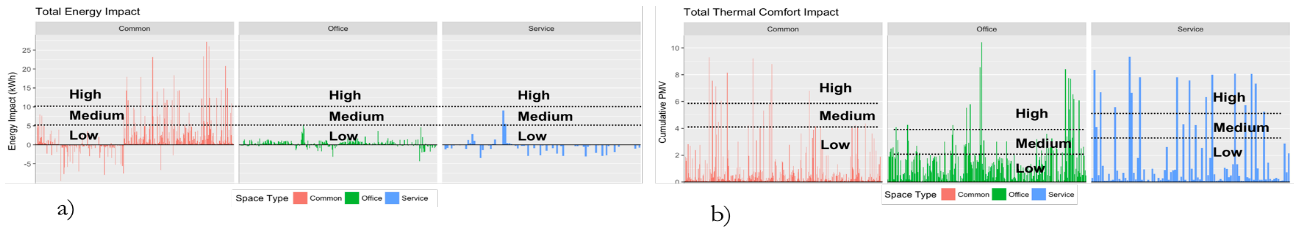


Figure 4 (a) Total energy consumption impact grouping and (b) total thermal comfort impact grouping.

In the example, office rooms have a lower threshold for thermal comfort impact than common spaces and service areas, meaning office rooms have more strict requirements for thermal comfort. With the normalization and grouping, the total impact of the alarms could be calculated with Equation (5).

$$Total\ Impact = A \times Energy\ Consumption\ Impact + B \times Thermal\ Comfort\ Impact \quad (5)$$

The grouping thresholds in Figure 4 and weighting factors A and B in Equation (5) can vary based on building operators' preferences. For example, if thermal comfort is more critical in a building, the grouping thresholds could be lower and factor B could be increased. Finally, a 3D visualization function is built upon the impact quantification results. It allows users to see the basic information of the alarms including building, floor, room, alarm type and occurring time. In addition, it provides the potential impacts on energy consumption and thermal comfort and the alarm priority. Figure 5 shows an example of the visualization.

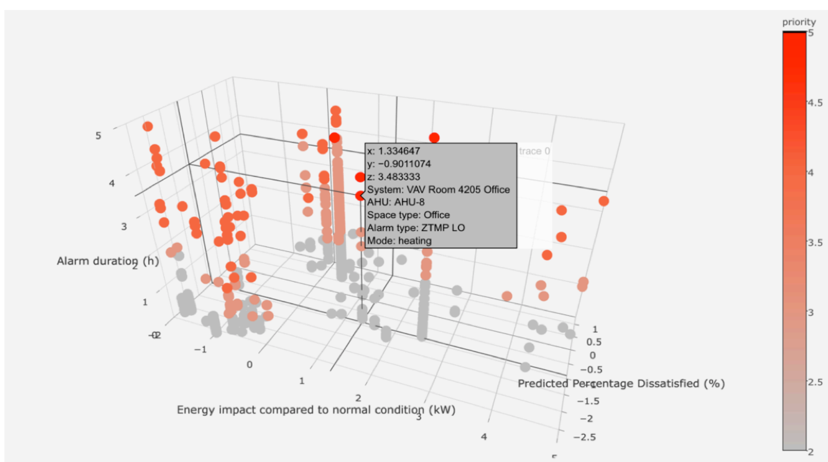


Figure 5 3D visualization of alarm information and priority.

The interactive visualization tool allows facility managers to filter out top alarms from the overwhelming number of trivial ones, and make more informative operation and maintenance decisions.

Discussion

As discussed before, there is very limited research on the BAS alarm management topic. The interview with facility managers also indicates the need for a better BAS alarm management function which provides alarm categorization and prioritization. This study has proposed a data-mining framework that helps to preprocess the raw alarm, categorize the alarms based on their affected objects and prioritize the alarms based on potential energy consumption thermal comfort impacts. The implementation of the framework is demonstrated by a case study of a building on CMU campus. In the case study, different impact metrics such as energy consumption and thermal comfort are weighted differently. The quantification results could be easily used to prioritize and visualize the alarms and their detailed information. With the visualization, facility managers can navigate to the top alarms with less effort than before and obtain key relevant information behind the scene.

In this paper, only occupant-related alarms are investigated. The potential energy consumption impacts of those alarms are quantified via first principle calculations. In buildings with detailed sub-metering, sensor data could be coupled into this framework for the impact quantification. Moreover, other impact metrics such as indoor CO2 level, operation cost, equipment life could be added to the framework to satisfy different user needs. Currently, the alarm prioritization is based on the alarm duration calculated from historical data. With the data preprocessing and feature reconfiguration methods proposed in this framework, a machine learning model could be developed to predict the durations and associated impacts of future alarms. The model would predict the duration of a certain alarm with its basic information, operation schedule and weather condition. Details of the developing and implementation of the machine learning model are presented in another paper by the authors.

In the future, one potential application is to integrate the framework into Computerized Maintenance Management System (CMMS). CMMS could receive real-time alarm log, sensor measurements, and weather data. It then feeds those data into the data-mining framework. After categorization and prioritization, top alarms in different categories could be shown to facility managers. Operation and maintenance workflows under certain alarm conditions could also be standardized.

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NOMENCLATURE

$\dot{Q}$ = Energy transfer rate between discharge air and room air (kW)

$\dot{V}$ = discharge air volumetric flow rate (m^3/s)

C_v = volumetric specific heat capacity of air ($kJ/m^3 \bullet K$)

$t_{discharge}$ = the VAV terminal discharge air temperature (˚C)

t_{room} = the room air temperature (˚C)

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