PROCESSES, INFORMATION REQUIREMENTS AND CHALLENGES ASSOCIATED WITH CORRECTIVE MAINTENANCE IN RELATION TO INDOOR AIR PROBLEM RELATED WORK ORDERS

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ABSTRACT

Even though many approaches have been proposed for automated fault detection and diagnosis of Heating Ventilation and Air Conditioning (HVAC) systems, and advanced maintenance programs, such as preventive and predictive maintenance have been applied for the systems, issuing work orders for corrective maintenance is still a reality. Currently corrective maintenance still accounts for more than 55% of all maintenance programs in average facilities in the US (DoE, 2010). Indoor air related problems are especially important among corrective maintenance work orders. This paper provides details of a case study conducted to capture the workflow that HVAC mechanics follow, their rationale in diagnosis process and the information they typically refer to while responding to indoor air related corrective maintenance work orders. The general workflow for HVAC mechanics to complete such types of work orders was summarized into 5 stages, and generic information requirements recorded from the case study were synthesized. Initial findings show two main challenges in the industry for HVAC mechanics to get access to required information, which highlights the need for a systematic approach that would enable identification of such information applicable to a given context under which a work order has been generated and provide values of required information for HVAC mechanics to do sound diagnosis through integrated data repositories.

KEYWORDS

Indoor air related problems, Corrective maintenance, Information requirements, Challenges

INTRODUCTION AND PROBLEM STATEMENT

One of the fundamental facility management services is responding to occupants' requests and solving problems reported on work orders, which is corrective maintenance. Though advanced maintenance programs have been proposed and used such as preventive, predictive and condition-based maintenance, corrective maintenance is still a reality and currently constitutes more than 55% of all maintenance activities in average facilities management organizations in the US (DoE, 2010). The barriers such as limited budget and human resources to put other types of maintenance programs into practice, and incompatibilities between existing HVAC systems and advanced algorithms, make corrective maintenance a de facto in the industry (DoE, 2010, Brambley et al., 2005). Among corrective maintenance work, indoor air related problems are especially important and require prompt attention because they directly affect occupants' productivity and health (Seppänen et al., 2006). Complaints of nature "it's too hot/cold" are among the top two complaints in offices according to a survey conducted by International Facility Management Association (IFMA, 2009).

Diagnosis of indoor air related problems is a complex process due to the increased complexity of modern HVAC and control systems, and changes in spaces or HVAC systems that might result in problems. There are tens or even hundreds of components in an HVAC system working together to maintain good indoor environments. The failure of a single HVAC component can result in indoor air related problems, and different components in an HVAC system, when failed, can result in similar consequences in a space. In a relatively simple system with only a single boiler, a hot water distribution and a related control system, 32 possible faults can cause a "too cold" complaint by occupants (Fletcher, 1999). Moreover, other than malfunctioning HVAC system components, many other factors, including building function alternations and interior layout changes, can result in occupant discomfort (Budaiwi, 2007). Information about these factors are needed by HVAC mechanics; however it changes as the problem, space and system characteristics associated with a work order change. However, currently, there is lack of a systematic approach in the industry for novice mechanics (and expert mechanics that are not familiar with given spaces or systems) to refer to and identify such information regarding the diagnosis task. In addition, such factors are rarely documented and stored in a usable format for mechanics to refer to for prompt resolution of corrective maintenance. HVAC mechanics usually have to make decisions with lack of information (Gnerre et al., 2007). As a result, responses to occupants' complaints are delayed, root causes remain unknown, and actions of good intentions cause further problems (Goins et al., 2012).

Many automatic fault diagnosis and detection (FDD) approaches or algorithms have been developed to identify and solve HVAC faults automatically. However, different FDD approaches all have their weaknesses and limitations (Katipamula & Brambley., 2005, Dash et al., 2000), and thus their applications are mostly seen in laboratories (Katipamula & Brambley et al., 2005). In addition, as mentioned above, many other factors such as building function alternations, interior layout changes, installation of new heat-generating office equipment, and occupancy number changes, could cause indoor air related problem even though HVAC systems are working perfectly. However, FDD approaches are designed to identify faults in HVAC systems, but are not able to identify these factors other than malfunctioning HVAC components.

A case study has been conducted with the purpose of understanding expert mechanics' rationale while responding to corrective maintenance work orders in relation to indoor air problems. The study involved shadowing work of 23 corrective maintenance work orders with expert HVAC mechanics in multiple campus buildings. The workflow that mechanics follow and information they refer to in each work order were captured and analyzed. Challenges in the current workflows have been identified. This paper provides initial findings in relation to the workflow, information requirements and industry challenges faced by HVAC mechanics while diagnosing indoor air related problems.

RESEACH APPROACH

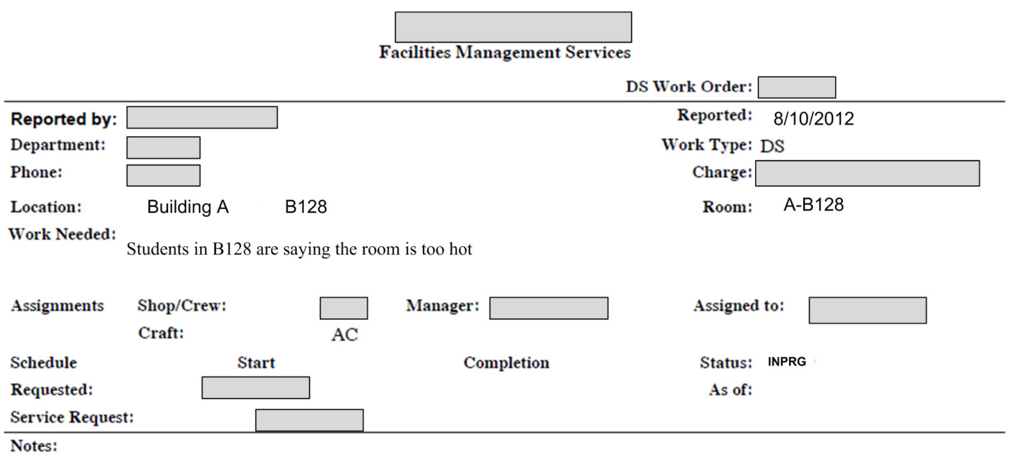
The case study has been conducted with Facilities Management Services (FMS) group in 4 campus buildings. During this study, 23 corrective maintenance work orders that were issued by occupants' complaints in relation to indoor air related problems were shadowed. Among these, 13 of them were related to temperature problems (e.g., too hot/cold), 6 of them were issued because of air flow problems (e.g., no air, too stuffy, too much air), 3 of them were associated with noisy HVAC components, and 1 of them was about humidity problem (e.g., humidity too high). To be able to systematically record the workflows, time allocated and information used for each work order, a template was designed and used throughout the study. This template includes the following fields for each work order: location of the reported problem, brief problem description, room type, flow of events followed by a mechanic, information needed by a mechanic in each event, and time spent on each event. A synthesis work has been done at the end of the study to analyze the patterns in workflows, information requirements and identify the challenges inherent in the current processes.

FINDINGS

General workflow to complete a corrective maintenance work order for indoor air related problems

Analysis of the flow of events captured during the shadowing works showed that the workflow for corrective maintenance for indoor air related problems can be decomposed into five main stages: (1) Receive a work order; (2) Perform a general check; (3) Perform a detailed inspection; (4) Perform testing; and (5) Deploy remedies. The descriptions of each stage of the workflow are provided below:

(1) Receive a work order. The process of diagnosing an indoor air related problem starts when Facilities Management Service receives occupants' complaints and assigns the work order to an HVAC mechanic. Figure 1 shows a real work order that an HVAC mechanic would receive. Values of some of the fields in Figure 1 have been disguised to protect information privacy.



Facilities Management Services

DS Work Order:

Reported by:
Department:
Phone:
Reported: 8/10/2012
Work Type: DS
Charge:

Location: Building A B128
Room: A-B128

Work Needed: Students in B128 are saying the room is too hot

Assignments Shop/Crew: Manager: Assigned to:
Craft: AC

Schedule Start Completion Status: INPRG
Requested: As of:
Service Request:

Notes:

Figure 1 – An example work order from the campus FMS

The basic information that an HVAC mechanic would need to get from a work order is "Location", which shows from which space the work order was generated, and "Work Needed", which shows a brief description of the reported problem and the symptoms associated with the problem, so that s/he can travel to the related space for troubleshooting or refer to the related data sources that would be helpful for the next stage.

(2) Perform a general check. This is a general inspection task that a mechanic would do once s/he arrives at the space that is associated with the work order or checking the data in related data sources (e.g., BAS parameters). This stage entails making sure that the problem really exists. Even for ideal indoor environments, complaints still can be reported and this step eliminates the complaints that were reported within the comfortable range defined by ASHRAE (ASHRAE, 2010). This step also aims at eliminating factors other than mechanical faults before

going into detailed inspection of an HVAC system. These could be obvious factors such as a thermostat being set to a wrong setpoint or installed in a wrong location for "too hot/cold" calls. Also, space related factors can cause indoor air related problems, such as a space being used for a purpose different than its design intent, with an occupancy number way different than its design capacity, or with various interior partitioning and alternations. Such factors are identified and checked during this stage.

(3) Perform a detailed inspection. After the factors other than mechanical faults that might lead to a reported problem are checked and eliminated, the mechanic will do a detailed inspection and tracing in the system to understand if the problem is due to a mechanical fault or not. S/he firstly needs to understand the control logic of the HVAC system, which is basically what are the components in the system and how they are working together, decides on which components could possibly be the problem source, and then locates the components to do further testing in the next stage.

(4) Perform testing. Once the mechanic decides on which component to check and locates the component, the mechanic will test if the component works as expected. This stage requires expertise in understanding the logic of mechanical systems. Equipment specifications are necessary if the mechanic is not familiar with certain equipment. The mechanic may need to test multiple components before pinpointing the malfunctioning one.

(5) Deploy remedies. After problem source has been identified, remedy actions will be taken to troubleshoot the problem. Remedy could be repair/replacement of malfunctioning components, adjustment of component statuses (e.g., open/close a valve, a damper, etc.), or adjustment of setpoints.

Challenges associated with getting access to required information when performing on corrective maintenance of indoor air related problems

<u>There is no systematic way of identifying information needed during corrective maintenance of indoor air related problems</u>

Table 1 provides basic information of two work orders as examples, and the information items HVAC mechanics need in each stage of the two work orders. It also gives the diagnosis results of the work orders and remedial actions. As seen from two work orders provided as examples in Table 1, analysis of the 23 work orders showed that different information items are required and collected by the mechanics as characteristics of the work orders change. For example in these two work orders, different information items were used because the two spaces associated with the two work orders had different characteristics. Work order 1, as indicated in Table 1, was reported for a chemistry lab that was composed of multiple zones. The HVAC mechanic wanted to know the room temperature distribution to find out which zone had the reported problem. He also referred to the air pressure differential because air in labs is usually kept at negative pressure and high negative air pressure can cause strong infiltration from exterior walls, which would potentially result in temperature fluctuations in a lab space. Work order 2 was reported for an office space, which has a large window facing south. He used this information as a clue and wanted to know the temperature fluctuation in a day for that room and see if the times when the sun radiation would have a peak had any correlation with the temperature fluctuations – and hence the "too hot" call.

Table 1 – Information requirements for two work order examples

#	Location	Problem description	Information requirements in each stage	Cause and remedy
1	Building A – 3203 Chemistry lab	Too cold	*Receive a work order*: location, problem description; *Perform on general check*: problem type, problem spatial level, space type, space zoning, temperature distribution, air pressure differential; *Perform on a detailed inspection*: HVAC system type, control type, control logics, applicable components' location/status; *Perform testing*: logics of mechanical system	*Cause*: reheat coil had no heat because steam was off *Remedy*: need steamfitter to check steam
2	Building B – 3124 Office	Too hot, thermostat not responsive	*Receive a work order*: location, problem description; *Perform on general check*: problem type, problem level, window size and orientation, temperature fluctuation in a day; *Perform on a detailed inspection*: HVAC system type, control type, control logics, applicable components' location/status, reheat valve's failure rate; *Perform testing*: logics of mechanical system	*Cause*: reheat pneumatic control valve could not be closed properly *Remedy*: Close the manual valve to alleviate discomfort; need a steam fitter to replace the broken pneumatic control valve

It was also observed that it is not only types of information that a mechanic would need change as the characteristics of the work orders change. Applicable components also change with different work orders because different types of HVAC systems are composed of different components. For example, when investigating temperature problems in a space controlled by a VAV reheat system, the reheat coil, valve and VAV damper would require attentions; while in a another space with an all-water system, radiator hot water pipe and valve are the components need to be checked. Even though two HVAC systems are the same type, their individual configurations can also be different. For example, there are two VAV systems' AHUs serving different floors in one of campus buildings. AHU1 has a discharge air damper but AHU2 does not. When an air flow problem occurs, the discharge air damper will be among the applicable components in AHU1 but not in AHU2. Failure to know that there is indeed a discharge air damper in AHU1 would result in neglecting one possible problem source.

Analysis of 23 work orders showed that the information that is necessary for mechanics during the diagnosis stage change when the following characteristics of work orders change: problem type (e.g., temperature, humidity, noisy HVAC system, air flow), problem spatial level (e.g., problem reported for a single room vs. for multiple rooms), HVAC system type (e.g., all-air, air-water, all-water), control type (e.g. manual, pneumatic, electronic, Direct Digital Control) and space type (e.g. office, lab, classroom, restroom). In summary, it was evident from the case study that the type of information an HVAC mechanic would need change, as the work order characteristics change. A major challenge faced by the FM industry is that there is no systematic approach in the industry to help for identification of what information to consider for a specific corrective maintenance task as the context under which a work order is generated changes.

There are issues with accuracy, accessibility and storage of the required information during corrective maintenance of indoor air related problems

An initial list of generic information requirements for HVAC mechanics to diagnose indoor air related problems was identified through synthesizing the 23 work orders shadowed, and categorized in four main groups: (1) Space related information. HVAC mechanics need to know space related information which is helpful to identify space related causes, such as space usage type (as-designed and as-is), occupancy number (as-designed and as-is), new installation of heat-generating equipment, interior layout (as-designed and as-is), and space enclosure (exterior wall, window, etc.) insulation condition. This set of information is usually stored in architectural drawings and Computer-aided Facility Management (CAFM) system. (2) HVAC static information. When HVAC mechanics decide to inspect HVAC system, they need to know the system type, the control type and logic, the equipment schedule and specifications, and the layout of air distribution, so that they can identify applicable HVAC components that could be cause of the reported problems and their locations. This set of information can be found in mechanical drawings and mechanical designed documents. (3) HVAC run-time information. HVAC mechanics need to know HVAC systems' sensor readings, parameter setpoints and equipment working status to figure out if a component is working properly. The HVAC run-time information can be found from Building Automation System (BAS) interface if it supports remote monitoring. (4) Historical information about spaces and HVAC systems. It was also observed from the shadowing work that HVAC mechanics refer to their personal familiarity and experience about spaces and HVAC systems, such as operational failure rate of a type of component, the renovation history of a space or system, and the operation and maintenance history of a component, which is not captured and stored in any structured data sources. Historical complaints log in a space is also important, which can be queried from Computerized Maintenance Management System (CMMS).

Observation from the case study shows that there are accuracy and accessibility issues with these data sources in providing the required information. Typically, architectural and mechanical drawings are important data sources, but drawings gradually become obsolete due to changes and renovations in the spaces and the systems, and are not capable of reflecting the as-is conditions, especially in old buildings. None of the 4 campus buildings in our case study had accurate as-is drawings. Thus, HVAC mechanics rely on visual inspections at field in order to understand the configuration of spaces and systems, which results in extra time being spent for accessing required information.

Building Automation System (BAS) is very helpful to figure out parameter setpoints, current values of parameters that are measured by sensors, and equipment statuses. In work order 1, the HVAC mechanic used the BAS that controlled the lab space to find the air pressure differential in the lab. If the value was abnormal, then the HVAC mechanic would test and inspect components that were related with air pressure. The problem with BASs is that BASs from different vendors are installed at buildings and even in the same building at different zones. For instance, there were 8 different vendors that provided products for the campus buildings in this case study. This resulted in time wastes during identification of which BAS to check for a given parameter in a specific space or system. On the other hand, not every BAS supports remote monitoring. Old buildings have pneumatic control systems which do not support remote monitoring (2 out of the 4 campus buildings in our case study use pneumatic control systems). In this case, filed inspection and measurement is necessary, which will cause additional time.

Additionally, HVAC mechanics' personal experience and familiarity are also very important because they know which components are more likely to be malfunctioning than others in a specific system and space, and then they can find problem source after testing few components. For example, as shown in work order 2, when the HVAC mechanic knew that a certain type of reheat valve was malfunctioning a lot in previous work orders he performed, he gave the reheat valve a higher priority in his checklist. However, such maintenance history related information is not formally captured and stored for future use.

Another essential historical information item for HVAC mechanics to know is if the HVAC system has been operated under an unusual mode, such as fire alarm testing, or shut-down of steam, chiller plants, AHUs due to various operation and maintenance requirements. These intentional changes to an HVAC system can lead to occupants' complaints. However, in current practice the communication of this important information mostly relies on ad-hoc conversations or phone calls. For example, the mechanic who was responsible for work order 1 was not aware of steam shut-down and had to waste one hour for detailed inspection of the HVAC components. Among the 23 work orders that were shadowed in this study, 5 of them were caused by intentional changes, and in 3 of these cases, the responsible mechanic was not informed about the situation, which resulted in waste of time. HVAC mechanics need to be aware of this type of information during the general check stage.

Table 2 provides a summary of the categorized information requirements for HVAC mechanics, the current formal information sources of the required information and associated issues of accuracy and accessibility in current practice.

Table 2 – Information requirements for HVAC mechanics and the problems in current practice

<table>
<tr><th>Categories of required information</th><th>Current formal information sources</th><th>Issues of accuracy and accessibility in current practice</th></tr>
<tr><td>Space related information</td><td>Architectural drawings; CAFM</td><td rowspan="2">Drawings and design documents were found generally obsolete and not accurate in 4 buildings involved in our case study. HVAC mechanics need to spend a lot of time on visual tracing and inspection on field.</td></tr>
<tr><td>HVAC static information</td><td>Mechanical drawings; BAS specifications</td></tr>
<tr><td>HVAC run-time information</td><td>BAS</td><td>Many old buildings using pneumatic control BASs do not support remote monitoring and control; and BASs from different vendors are installed even in the same building, which result in time waste to identify which BAS to check for a specific space.</td></tr>
<tr><td>Historical information about spaces and HVAC systems</td><td>CMMS</td><td>Historical information was not formally captured. HVAC mechanics rely on personal experience and recall, and ad-hoc conversations with colleagues.</td></tr>
</table>

Furthermore, even though the existing data sources store accurate information, because the required information is stored in discrete data sources, it will still be time-consuming to collect necessary information from each of the data sources by HVAC mechanics manually. This significantly impacts the work efficiency. Our time study during the shadowing work shows that if information is readily available to the mechanics (either through personal recall or easy accessibility in related sources), an HVAC mechanic would only need 15 minutes on the average to diagnose the problem while s/he would need 2 hours or longer if information was missing and there were data accessibility issues.

As a summary, we observe that HVAC mechanics need to collect various information items before identifying the problem source and deploying corresponding remedies. It is a known fact that many factors can result in the same reported complaint for indoor air related problems, and in order to efficiently identify the source of the problem, an HVAC mechanic needs to collect evidences or clues (Burton, 1993), and then narrow down the search space of the source of the problems. These evidences and clues are information requirements that HVAC mechanics would need in order to diagnose indoor air related problems. However, our findings in this case study showed that information requirements for different work orders are changing but there is no systematic way of identifying them for HVAC mechanics. In addition, there are issues with accuracy, accessibility and storage of the required information. Under these circumstances, and given the fact that a HVAC mechanic can be responsible for multiple buildings and receive as many as 100 work orders in a month according to our case study, it is difficult for HVAC mechanics to manually define what information needs to be checked for each work order and collect the information from fragmented sources.

CONCLUSION

Corrective maintenance work order is inevitable and important, but diagnosis of indoor air related problems is a complex process because there are too many possible factors can cause the same problem symptom. A case study has been conducted to understand expert HVAC mechanic's rationale to do the diagnosis. Five stages of the diagnosis process are summarized and described. It was found that various information items are required in the process. The required information can be grouped under 4 main categories: space related information, HVAC static information, HVAC run-time information and historical information about spaces and HVAC systems. Two main challenges were observed in relation to getting access to the information required during the diagnosis of indoor air problems: (1) information that mechanics would need during diagnosing changes as the problems, spaces and systems associated with work orders change, but there is no systematic way of identifying information under specific context, and (2) there are issues with accuracy, accessibility and storage of the required information during corrective maintenance of indoor air related problems. These identified challenges provide a motivation for a research towards the development of an approach to enable identification of applicable information requirements given a work order's context of problem, space and system characteristics, and integration of discrete sources into a repository to generate values for the required information to support HVAC mechanics' corrective maintenance of indoor air related problems.

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