Carnegie Mellon University

CARNEGIE INSTITUTE OF TECHNOLOGY

THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF Doctor of Philosophy

TITLE A Formal Approach to Provide Information Support for Troubleshooting of HVAC Related Problems

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ACCEPTED BY THE DEPARTMENTS OF

Civil and Environmental Engineering

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A formal approach to provide information support for troubleshooting of HVAC related problems

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Department of Civil and Environmental Engineering

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December, 2014

Acknowledgements

This dissertation is the final product of my three-year's PhD research work at Carnegie Mellon University, but it would not have been possible without the help from many great and brilliant people. First I want to express my greatest appreciation to my academic advisor, Semiha Ergan, who has taught me how to do research and guided me through the course of my PhD research. I not only learned research skills, but also many precious qualities and attitudes from her, such as being proactive and persistent to achieve goals. I'm very grateful for her patience, support, valuable advices and feedbacks.

My sincere appreciation also goes to my committee members, Burcu Akinci, Mario Berges, Anind Dey and Xuesong Liu. They have kindly dedicated much time on reviewing my research framework, methods and findings since my research proposal, and kept providing valuable and constructive feedbacks for me to improve the quality of my dissertation. I have benefited a lot from their insightful questions and suggestions.

I also want to thank my officemates, Engin Burak Anil, Te Gao, Bo Gu, Varun Kumaraswamy, Varun Kasireddy, and Raghuram Sunnam, for their company and encouragement, which are very important for me, especially when I had difficulty in progressing with my research.

Many thanks to the staff at Carnegie Mellon's Facilities Management Services, and University of Pittsburgh's Facilities Management Division. Thank Martin H Altschul and Albert A Agostinelli for the support of my research and coordination, and thank all the HVAC mechanics I have talked to for their time and contributions to my research findings.

Thank CEE staff for making a great community. Thank CEE department and Pennsylvania Infrastructure Technology Alliance (PITA) for providing the financial support of my research.

Finally, I would like to thank my family, my dear parents and husband. My parents, Xianqi Yang and Yuling Xue, always trust every decision I make and support me to pursue my dream, even it means they have to be separated from their only child for many years at the other side of the world. My husband Jianan Jiang who is also my soul mate and best friend, has always been by my side during good and bad times. He has dedicated a lot to make my PhD life easier and happier.

Executive Summary

Currently, corrective maintenance constitutes more than 55% of all maintenance activities in average facilities management groups in the US and. Among corrective maintenance activities, heating, ventilating and air conditioning (HVAC) related problems require prompt attention because people spend about 90% of their time inside buildings and such problems directly affect occupants' productivity and health. However, troubleshooting of HVAC related problems is still recognized as a complex and challenging task due to the lack of apparent causes of the problems and information access/verification issues during the troubleshooting process. Three specific challenges this research addresses include: (a) the lack of knowledge of work order characteristics that result in change of possible causes of reported problems and the lack of a formal definition of domain information for troubleshooting HVAC related problems; (b) the lack of a formalism that systematically reduces the search space of possible causes, and data access issues due to dispersed data storage; and (c) the lack of efficient ways for HVAC mechanics to synthesize and comprehend information for decision-making during troubleshooting of HVAC related problems.

In order to address the challenges stated above, this research aims to develop a framework which can enable identification, retrieval and visualization of the information that is required for troubleshooting of HVAC related problems. To develop such a framework, the research work I have done includes (1) identifying generic information requirements that HVAC mechanics need during troubleshooting of HVAC related problems and characteristics of work orders that affect applicable information requirements for a given work order; (2) development of representation schema and reasoning mechanisms to automatically identify applicable causes and retrieve relevant information for a given work order; and (3) evaluation of the efficiency improvement of the decision-making process during tasks of troubleshooting HVAC related problems using visualization platform.

The research findings have been validated in terms of: (1) the *generality* of the identified information requirements of HVAC mechanics and the characteristics of work orders for troubleshooting of HVAC related problems; (2) the *efficiency* and *accuracy* of the developed formalism in identifying applicable causes and retrieve information for different work order contexts; and (3) the *efficiency* improvement using an integrated visualization platform in the process of troubleshooting of HVAC related problems.

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Chapter 1. Introduction

Corrective maintenance (CM) has been the predominant maintenance mode in the US. CM typically gets more than 55% of the resources allocated for facilities management (FM) in an average facility in the US (DoE, 2010). Although some work orders that fall under corrective maintenance may be eliminated by conducting other maintenance programs, such as preventive and condition-based maintenance, these advanced maintenance programs have barriers for implementation due to the limited budget and human resources reserved for FM (DoE, 2010). Issuing work orders and troubleshooting problems in response to HVAC related problems, such as "too hot/cold", are still among the top services for FM groups in office buildings (IFMA 2009). HVAC problem related work orders require prompt attention because people spend about 90% of their time inside buildings and such problems directly affect occupants' productivity and health (EPA 1989; Seppänen & Fisk, 2006).

An HVAC related corrective maintenance task usually starts with a complaint (e.g., too hot/cold) being reported by occupants, and then the Facilities Management (FM) division issues a work order and assigns it to HVAC mechanics, who will be responsible to check the reported spaces and HVAC systems to troubleshoot the problems (Yang and Ergan 2013). The investigation of HVAC related problems is a complex and challenging task due to the lack of apparent causes of the problems (Burton 1993) and information access/ verification issues (Gallaher et al. 2004). Lack of information support is a known issue in the FM industry: $1.5 billion is wasted because maintenance staff stays idle while waiting to access information to address maintenance issues and $4.8 billion is spent on information verification and validation (Gallaher et al., 2004) in capital facilities in the US in a year. Work efficiency of HVAC mechanics is significantly reduced as they have to make decisions with insufficient information and limited understanding of the problem (Gallaher et al., 2004; Gnerre et al. 2007). Under such circumstances, responses to occupant complaints are delayed and root causes are left undiscovered (Goins and Moezzi 2012).

Many automated Fault Detection and Diagnosis (FDD) or automated commissioning approaches have been proposed to identify and solve faults in HVAC systems. These approaches would enable advanced maintenance activities, such as predictive maintenance and condition-based maintenance, but they are rarely used in real life settings due to various limitations, such as the need for large data sets to train or develop the mathematical or machine-learning models, or the need for generalized approaches that can be used for HVAC systems with different types and configurations (Katipamula and Brambley et al. 2005). In addition, many factors such as building function alternations and space layout changes can cause occupant discomfort other than the malfunctioning HVAC systems (Budaiwi, 2007; Morton, 2012); however, FDD approaches are generally designed to identify HVAC system faults, but not necessarily for identification of various other factors that could cause indoor thermal discomfort. Therefore, corrective maintenance, i.e., troubleshooting of reported problems by HVAC mechanics is still indispensable part in FM practice and requires attention.

Shadowing of experienced HVAC mechanics on 40 work orders from a FM group showed that inefficiencies exist in the current practice of troubleshooting HVAC related problems, and such inefficiencies are mainly caused by the lack of information support. However, in the current practice there is no formal and systematic way of identifying applicable causes and providing the required information for HVAC mechanics, and even experienced HVAC mechanics miss required information and as a result waste time. One of the challenges is the fact that the applicable causes and required information for a given work order vary with the context of a reported problem, specific space and HVAC system associated with that work order (Yang & Ergan 2013). Another challenge is the lack of prompt accessibility to the required information for HVAC mechanics and residing of this information in different sources. Even if the information sources are available, it is a known fact that they are often inadequate due to the lack of coordinated mechanisms to synthesize data from discrete sources (National Research Council 2009). The required information for the troubleshooting needs to be perceived by the mechanics in an intuitive way for correct decision making. My user studies with HVAC mechanics and facility operators in two FM groups showed that how the data is displayed and presented to the users affects the efficiency and accuracy to complete tasks. This study only used BAS as the information source to display, given that there are various other data sources that need to be accessed and used for troubleshooting HVAC related problems, the information overloading problem will be exacerbated if the generated information is not displayed in appropriate forms. Therefore, there is a need for a formal approach to (a) identify applicable causes and required information for a given work order, (b) retrieve the values for these requirements, (c) and visualize them in relation to the space and the HVAC system.

The objective of the proposed research is to develop a framework which can enable identification, retrieval and visualization of the information that is required for troubleshooting of HVAC related problems in spaces served by centralized HVAC systems. The proposed approach consists of three modules as provided in Figure 1. The approach builds on a data representation schema, which is used to identify applicable causes and information requirements for a given

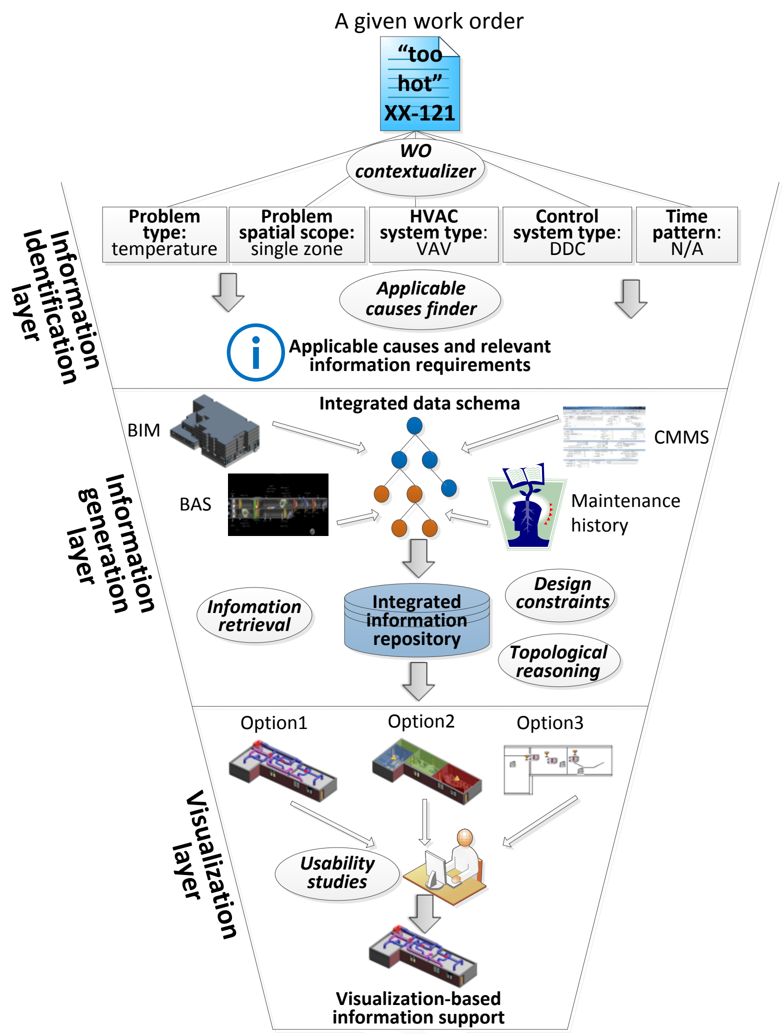


Figure 1. An over the approach

work order. An integrated information repository enables populating values for the identified information requirements for the context of a given facility. The representation schema was developed as part of this research by augmenting semantically rich building information models (BIMs). BIMs can store facility information in a computer interpretable way and has been used to store facility histories, necessary design, construction and FM information (Eastman et al. 2008). However, the use of BIM to support troubleshooting of HVAC related problems has not been studied yet. The final step includes development of a visualization-based environment for HVAC mechanics to perceive and comprehend the required information in relation to the space and system under investigation without information overloading. Visualization is important to see patterns and trends in large data sets (Gershon et al. 1998), to effectively identify useful information from retrieved set of candidates (Newby 2002) and acquire knowledge as compared to text-based presentation (Keller et al. 2006). However, different ways of visualizing the identified information in relation to spaces and HVAC systems and how much efficiency these can improve the troubleshooting process need to be studied.

The following sections describe the motivating case study, challenges and engineering problems in the current industry practice for troubleshooting HVAC related problems, vision of this research, and the overall assumptions and the scope of the proposed research.

1.1 Motivating case study

I have conducted a motivating case study with a campus FM group, with the purpose of understanding the current practice of troubleshooting HVAC related problems in response to occupants' requests. The case study included shadowing and observation of experienced HVAC mechanics while they were working on forty HVAC related work orders in six different campus buildings. To systematically record the practice followed by the HVAC mechanics to troubleshoot the reported problems, a data collection template was designed and used throughout the shadowing work. The template included work order details, such as the reported problem description, the reported time, the reported space ID, and the sequential list of actions conducted by the HVAC mechanics, total time spent and information required in each action. HVAC mechanics that were shadowed had more than twenty years of experience in HVAC maintenance domain. Table 1 gives an overview of the six buildings that had issues and the forty work orders shadowed.

Table 1. Overview of the shadowed work orders and the buildings

Buildings	Building A	Building B	Building C	Building D	Building E	Building F
Building age	98	103	41	75	28	82
Number of shadowed work orders	6	9	9	13	1	1
Types of the HVAC systems	All-air single-duct VAV type; All air single-duct CAV type; Air-water (radiator) type	All-air single-duct VAV type; All air single-duct CAV type; Air-water (FCU) type	All-air single-duct VAV type	All-air single-duct VAV type; All air single-duct CAV type	All-air single-duct VAV type	Air-water (FCU) type
Reported problems	12 temperature problems 6 air flow problems 1 humidity problem 4 HVAC noise problems 2 HVAC leakage problems			10 temperature problems 2 air flow problems 1 humidity problem 1 HVAC leakage problem 1 odor problem		

A synthesis work has been done at the end of the shadowing work to analyze patterns of actions performed and information used by HVAC mechanics. As a result, the following patterns have been observed in the current practice:

(1) Even experienced HVAC mechanics miss required information and as a result waste time

Even though the participating HVAC mechanics had decades of experience, there were still cases where the mechanics missed key information items at the first place, and as a result, wasted time. Table 2 and 3 shows two such examples.

Table 2. Example work order 1 where a key information was missed

Work order 1: Building D, room 304, "too warm";

Responsible person: HVAC mechanic A, who had 37 years of experience and was familiar with the facility

Actions conducted by the HVAC mechanic	**Time (min)**	**Components checked and/or required information**
Went to the reported room; knew this room was controlled by a Constant Air Volume (CAV) system using pneumatic control	N/A	Type of the HVAC system Type of the control system
Checked the pneumatic thermostat in the room; found the set point was at 70 ℉ while the current temperature was at 80 ℉	3	Thermostat: location, set point, current temperature reading
Checked the control panel and found that the pneumatic air pressure sent from the thermostat was too low (4 psi, which should have been at 13 psi) in order to open the chilled water valve properly Assumed that the main pneumatic air-line had a leak and thus the reason for not having enough air pressure supplied to the thermostat	12	Chilled water valve: location, control command reading
Opened the ceiling tiles to check the main air-line but found no leak	**26** *	Pneumatic airline: location
Found a drawing of pneumatic air-line and the drawing showed that there was another branch air-line connecting to the thermostat which controlled a steam valve	15	**Thermostat: control relationships;** **Steam valve: control relationships**
Assumed that the steam valve was leaking pneumatic air; traced the pneumatic air-line in order to find the steam valve but could not find it	**33**	**Steam valve: location**
Located the connection point of the branch air-line to steam valve and disconnected it; the pneumatic air pressure sent from the thermostat to the chilled water valve reached to 13 psi	9	N/A
Generated a new work order for a steamfitter to fix the steam valve	N/A	N/A
Time wasted	**57%**	

Table 3. Example work order 2 where a key information was missed

Work order 2: Building C, room 3202, "low air flow in the lab";

Responsible person: HVAC mechanic B, who had 29 years of experience and was familiar with the facility

Actions conducted by the HVAC mechanic	**Time (min)**	**Components checked and/or required information**
Went to the room; knew this room was under pneumatic control	N/A	Type of the control system
Located two supply air diffusers and two exhaust air grilles; found that the supply air flow was fine but two exhaust grilles were very dirty, and one of them had low air flow, while the other one had air blowing out instead of sucking air in	12	Supply air diffusers: location, supply air flow rate reading Exhaust air grilles: location, exhaust air flow rate reading
Disassembled and cleaned the two exhaust grilles	45	N/A
The exhaust air grille with the low air flow had normal air flow, but the other one still had opposite air flow	5	Exhaust air grilles: exhaust air flow rate reading
Was not sure why the air flow direction was wrong; traced the ductwork from the exhaust air grille and finally found that a damper in the duct was stuck at close position	**<u>67</u>**	**Exhaust air damper: location, percentage of opening**
Adjusted the damper to open position	8	N/A
Time wasted	**49%**	

*Note: The time that was wasted because of lack of information was highlighted in bold and underlined. The missed information was shown in bold.

In the shadowed work order 1, which was reported for a temperature problem, HVAC mechanic A did not know that the thermostat also controlled and connected with a steam valve, and as a result he made a wrong assumption about the main air-line as leaking and wasted time in inspecting the leak in the main air-line. When he realized that the steam valve could be the source of the problem and needed to check the valve, he did not know where the valve was and also wasted time trying to find the valve. In the shadowed work order 2 with the air flow problem, HVAC mechanic B found that the exhaust air flow direction was wrong, but he did not know what HVAC component could be the cause and had to spend a long time tracing the ductwork inch by inch, until he finally found a stuck damper in the duct. In both of the cases, the time spent on non-value adding actions due to lack of information, such as inspecting a wrong component, and tracing ductwork to locate a component, was around 50%. The tables show only two examples, however around half of these work orders had similar problems.

It was found from the shadowing work that in the current practice, there is no formal and systematic way for HVAC mechanics to identify what component to check and what information to collect for a given work order. The identification of required information for a given work order is left to the judgment of the HVAC mechanics, and mostly depends on the responsible mechanics' experience levels and familiarity with the spaces and systems (Yang and Ergan 2013; Espíndola et al. 2013). Information items that would be the key to pinpoint the problem were missed at the first place by the mechanics who were not familiar with the systems or the spaces, which would result in more time being spent on the problem. Hence, there is a need for studying the information requirements of HVAC mechanics for troubleshooting of HVAC related problems in order to understand what information needs to be made available to HVAC mechanics.

(2) Applicable causes and information needed during troubleshooting of HVAC problems change with the characteristics of work orders

An analysis of the shadowed work orders showed that as certain aspects of the work orders change, the set of possible causes and information items that are required for a given work order also change. For example, in the work order 1, which had a temperature problem, the thermostat, the chilled water valve and the steam valve were checked as possible cause of the problem and the information associated with these components were required, because these components constitute the set of components that are related to temperature control in an HVAC system and could be the causes for the temperature problem. In comparison, in the work order 2 that had an air flow problem, the supply air diffuser, the exhaust air grille, and the exhaust air damper in the HVAC system were checked and information associated with these components were used, because these components directly controls the air flow in an HVAC system and thus are among applicable causes for air flow problems.

Similarly, it was observed that the type of HVAC systems also affects information requirements of HVAC mechanics. For example, the opening percentage of a Variable Air Volume (VAV) damper would be required for a temperature problem in a space served by VAV type of HVAC system, while such information is not required for the same problem reported in another space served by a Constant Air Volume (CAV) type of HVAC system because VAV dampers do not exist in CAV systems. Hence, there is a research need to understand the characteristics of HVAC related work orders that affect applicable causes and information requirements, in order to bring a systematic approach to identify the customized set of causes and information requirements for a given work order.

(3) Required information and their values are not readily available for HVAC mechanics and reside in different data sources

While doing shadowing work with HVAC mechanics, I also investigated where the information they need reside and how they access to them. I found out that in current practice the information requirements are defined and collected by HVAC mechanics in an ad-hoc and document-based manner because the required information is not readily available and provided in a systematic way. Even experienced HVAC mechanics lost track of required information, which resulted in inefficient performance such as delays in completing the work order or waste of time during the troubleshooting process.

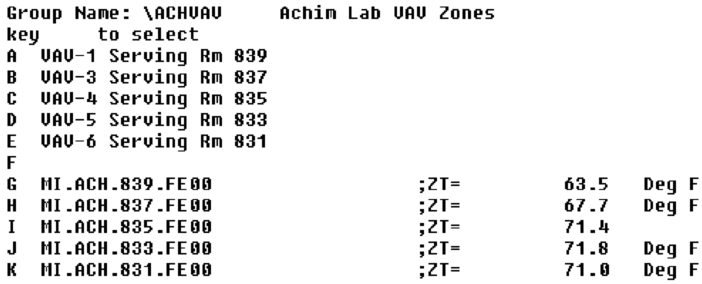
Closer examination of the sources of the required information of HVAC mechanics shows that the information resides in disparate data sources. It is important for HVAC mechanics to be aware of space related information, such as space usage type, layout of space thermal zones for the reported temperature problem. The space related information is usually provided in as-built architectural drawings and Computer-aided Facility Management (CAFM) systems. When HVAC mechanics need to inspect HVAC systems, they want to know type of the HVAC systems, for example, whether the HVAC system is a Constant Air Volume (CAV) type, Variable Air Volume (VAV) type, or Variable Air Volume with perimeter heating type, etc. They also need to know the type of the control for the HVAC systems, for example, pneumatic system, or electric system. In addition, other required information includes the control relationships between HVAC components, the location of HVAC components and the layout of air distribution. Such as-designed system information is stored in mechanical drawings and related documents such as equipment schedule and specifications. At the same time, they need HVAC run-time information to figure out if equipment is working properly, for example, the supply air temperature and the reheat valve percentage of opening. Such information includes sensor readings of measured parameters, setpoints of controlled parameters and equipment working status, which are provided by Building Automation Systems (BASs). In addition, during the field investigations, HVAC mechanics also referred to their personal experience and familiarity with the spaces and HVAC systems, such as the failure frequencies of a type of component and the maintenance history of a component. Historical work orders can be queried from Computerized Maintenance

Management Systems (CMMS). In summary, required information for investigating HVAC related problems is stored in different sources of documentation or systems.

Given the fact that the required information is not readily available and stored in fragmented way, and an HVAC mechanic can be responsible for multiple buildings and receive as many as 100 work orders in a month (based on the case study with campus FM group), it is very challenging for them to individually keep track of different data sources and manually collect the required information for each of the work orders, which results in information accessibility problem. Hence, there is a need for a systematic approach to generate the required information for HVAC mechanics given HVAC problem related work orders.

(4) It is unclear how visualization of the required information can affect the efficiency of the decision-making processes for troubleshooting HVAC related problems

Comprehending the situation and pinpointing the problem source require perceiving the necessary information in an efficient way (Bahrami et al. 2007). The required information will result in information overloading rather than comprehension of the situation if it is not displayed in appropriate forms to the HVAC mechanics. For example, in one particular building involved in the initial case study, there are 4 BASs in different areas. If we take one of the required information, i.e., “space temperature values” in work order 2 as an example, Figure 2.1-Figure 2.4 show the interfaces of different BASs to display this same information:



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Group Name: \ACHVAV     Achim Lab VAV Zones
key      to select
A   VAV-1 Serving Rm 839
B   VAV-3 Serving Rm 837
C   VAV-4 Serving Rm 835
D   VAV-5 Serving Rm 833
E   VAV-6 Serving Rm 831
F
G   MI.ACH.839.FE00                  ;ZT=        63.5   Deg F
H   MI.ACH.837.FE00                  ;ZT=        67.7   Deg F
I   MI.ACH.835.FE00                  ;ZT=        71.4
J   MI.ACH.833.FE00                  ;ZT=        71.8   Deg F
K   MI.ACH.831.FE00                  ;ZT=        71.0   Deg F
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Figure 2.1 Interface to show space temperatures in BAS1 using a tabular format

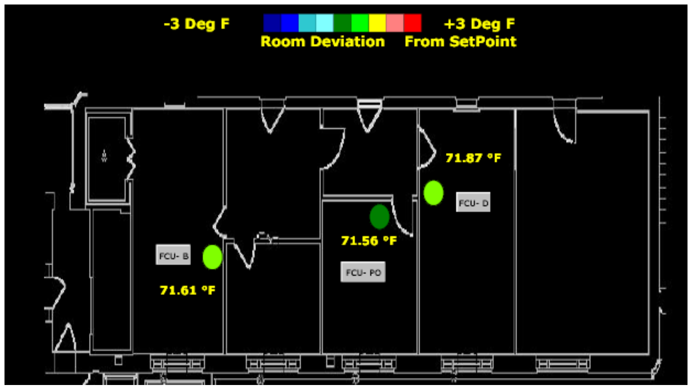


Figure 2.2 Interface to show space temperatures in BAS2 using color coded icons

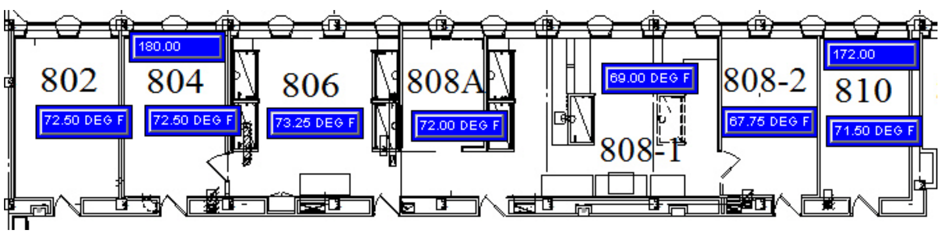


Figure 2.3 Interface to show space temperatures in BAS3 using text annotations

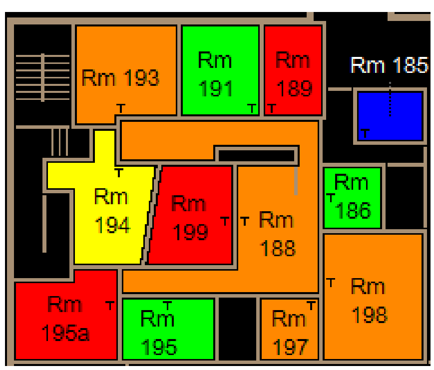


Figure 2.4 Interface to show space temperatures in BAS4 using color coded floor plans

Figure 2. Sample set of BAS interfaces to display space temperature readings

As seen in Figure 2.1-Figure 2.4, various BASs utilized in the campus buildings, the same information has been displayed with various ways (e.g., tabular format, color coded icon, text annotation, etc.). From my interactions with HVAC mechanics, I found they had different preferences on these different interfaces in comprehending space temperature, however the general consensus in their responses to my inquiries was that they prefer the interfaces where they can comprehend the situation at a glance as compared to detailed reading. They like BAS4 the best because they can quickly get an idea of the current status of space temperatures, while this information is less efficiently presented in other interfaces, especially in BAS1, where they spent longer time to comprehend space temperatures. Though various visualization techniques have been used in commercially available BASs, their impact on the situation awareness of HVAC mechanics is not clearly known. Thus, there is a need for understanding what the different options are to visualize required information for HVAC mechanics and how much the efficiency of HVAC mechanics' decision making processes can be improved by visualizing the required information per their preferences.

1.2 Challenges and underlying engineering problems

This section summarizes the challenges in the current practice and the corresponding research needs:

(1) *Lack of knowledge of work order characteristics that result in change of possible causes and lack of a formal definition of domain information*. I have found from the motivating case study that applicable causes and information requirements for troubleshooting of HVAC related problems change as characteristics of work orders change. Currently the identification of applicable causes and required information for different work orders is conducted manually by HVAC mechanics, and as a result it is observed from my case study that even experienced

HVAC mechanics wasted time when they were not familiar with the spaces and systems. Hence, there is a need for studying the information requirements of HVAC mechanics for troubleshooting of HVAC related problems in order to understand what information needs to be made available to HVAC mechanics. In addition, characteristics of work orders should be investigated to bring a systematic way of identifying applicable causes and information that HVAC mechanics would need to consider while troubleshooting different HVAC related problems.

(2) *Lack of a formalism that systematically reduces the search space of possible causes, and data access issues due to dispersed data storage*. Troubleshooting HVAC related problems is recognized as a challenging work because many possible causes could result in the same symptom for a reported problem, and various facility specific information that needs to be collected as evidence is not readily available. There are two research needs: (a) the need to provide customized set of causes for a given HVAC related problem, in order to reduce the search space and the possibility of neglecting root causes for HVAC mechanics; and (b) the need to provide required information for the reported problem, so that HVAC mechanics don't have to waste time on manually collecting required information from different sources.

(3) *Lack of efficient ways for HVAC mechanics to synthesize information for decision-making of troubleshooting HVAC related problems.* Work efficiency of HVAC mechanics in comprehending the required information changes with different ways the information is displayed to them. Visualization can enhance human's perception and comprehension of information. However, there is currently a lack of understanding on how much the efficiency of the troubleshooting process can be improved by providing the information in visual forms. There is a research need

to explore different ways of visualizing the required information to HVAC mechanics and conduct user studies to understand how much efficiency can be achieved by visualization.

1.3 Research vision

The objective of the proposed research is to develop a framework which can enable identification, retrieval and visualization of the required information for troubleshooting of HVAC related problems. Figure 3 shows the proposed research approach in an IDEF0 diagram.

The envisioned framework is composed of three modules. The first module [Figure 3 (a)] gets two inputs: a work order and a BIM. More specifically, the work order provides the type of reported problem and space ID(s), and the BIM is an Industry Foundation Classes (IFC) file which includes information about a specific facility, the reported space(s) and the associated HVAC system. The approach firstly uses these two inputs to generate the characteristics of work orders. The values assigned to the five work order characteristics – the type of reported problems, the spatial scope of reported problems, the type of HVAC systems, the type of control systems and the time pattern of reported problems together define a work order's context. Then the module will use the generated work order's context and a predefined matrix, which will be generated as part of this research between the library of causes for HVAC related problems and the work order contexts, to identify a set of generic applicable causes for the given work order context. Different applicable causes will require different set of information to be retrieved.

The second module [Figure 3(b)] gets additional data sources including work order history exported from CMMS, dynamic data exported from BAS and as-designed space information to populate an information repository about the spaces and HVAC systems for the inputted facility. It also gets the set of generic applicable causes identified from the second module, and further refines the applicable causes by matching the generic components to specific instances in the inputted BIM. While matching the components, the algorithm automatically identifies the instances of HVAC components that are of the same type but with different functionalities represented in BIM based on the standard HVAC design requirements. Once the specific cause instances have been refined, it finally retrieves the information that should be provided regarding the causes.

Final module [Figure 3(c)] will provide a visualization-based information support for efficient comprehension of the information generated from the second module in relation to space/system being investigated. In this step, different visualization techniques will be explored and mapped with different information items to develop multiple design options. I will use a user-centered and iterative process to design and implement a visualization platform to support troubleshooting of HVAC related problems. The final visualization platform will be evaluated through user studies with quantitative metrics.

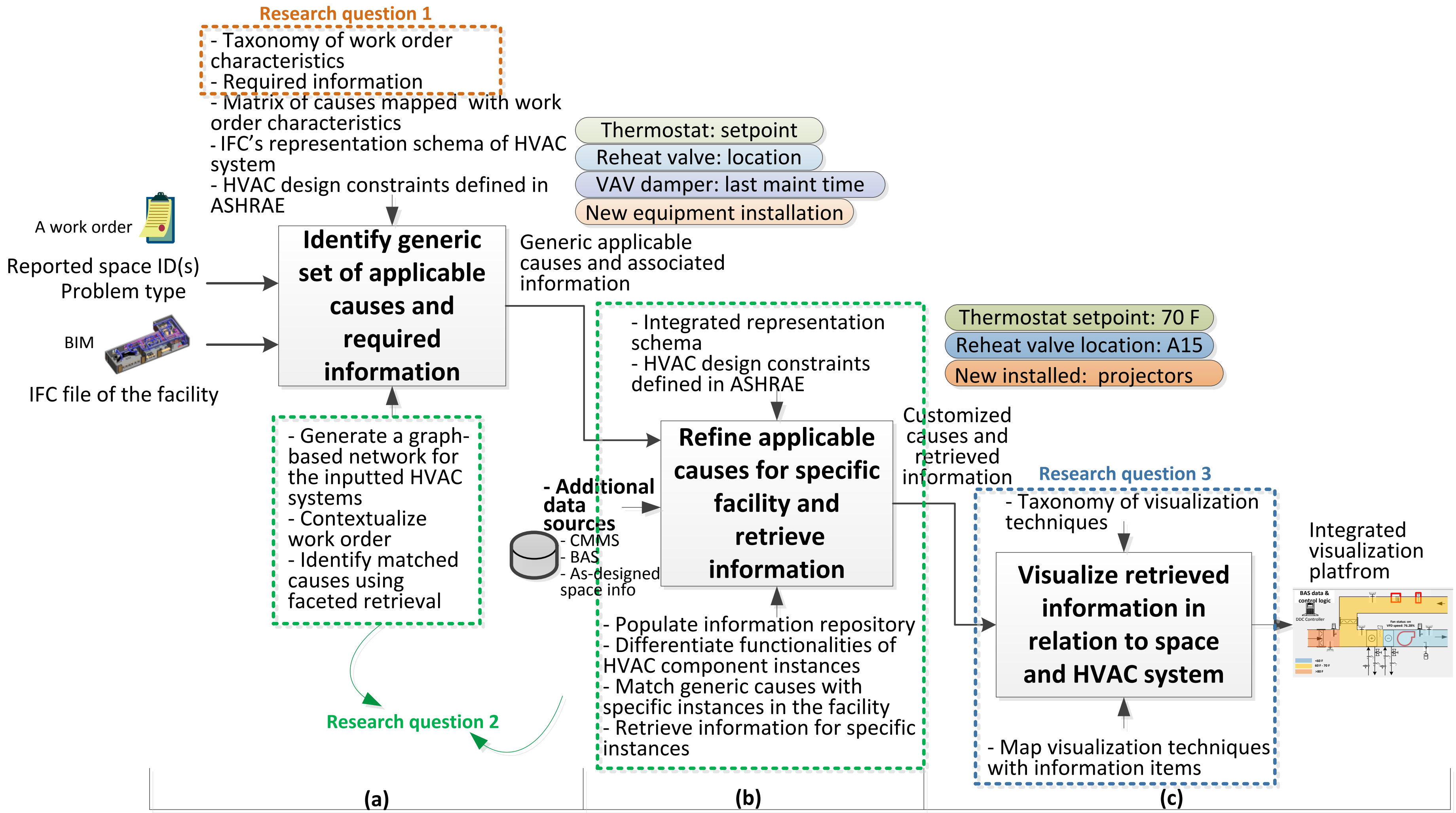


Figure 3. IDEF0 diagram for the envisioned approach

1.4 Overall assumptions and scope of the proposed research

The assumptions of this research are:

- Data sources, including Building Information Model (BIM), Building Automation System (BAS), and Computerized Maintenance Management System (CMMS) of the facilities in the testbeds, which are needed to generate the integrated information repository, are available for a facility. This assumption is valid because BIM can be developed from drawings, and BAS and CMMS are commonly used in current FM industry. Data from BAS and CMMS is exported and stored in .csv files.
- Users of the developed approach are HVAC mechanics who have background knowledge to troubleshoot HVAC related problems.

The scope of this research:

- This research focuses on work orders with HVAC related problems that are commonly performed by HVAC mechanics in response to occupants' requests in non-residential buildings with centralized HVAC systems. This type of work orders is among the mostly common service requests in a facilities management group for commercial buildings (IFMA 2009), and is among daily job responsibilities of HVAC mechanics. Indoor air quality problems that cause occupants' health related symptoms such as headache, fatigue, cough, shortness of breath, etc., are not within the scope of this research because it usually requires external experts or agencies to do the investigation, while is not among the daily responsibilities of HVAC mechanics.
- The scope of the research is only on centralized HVAC systems as centralized HVAC systems are more complex in configuration as compared to unitary and refrigeration-based

HVAC systems (e.g., window AC) and focusing on centralized HVAC systems will provide a larger scope as compared to others. Similarly, HVAC preventive maintenance work orders generated at regular intervals for a specific equipment asset, which do not require diagnosis work, are not within the scope of this research.

- The HVAC components that this study focuses on are mechanical components in HVAC systems. The electric and pneumatic components as part of the control systems are beyond the scope.

1.5 Research questions

This section discusses three research questions that target at addressing the challenges discussed before.

RQ1: What are the information requirements for HVAC mechanics when troubleshooting HVAC related problems and the characteristics of work orders that affect the information requirements?

I have found from my motivating case study that even experienced HVAC mechanics are not always aware of required information when responding to different work orders and as a result waste time. The same problem of lack of information would be exacerbated when new maintenance staffs are hired, or HVAC mechanics are assigned to other buildings to cover the shifts. There is need for a systematic approach to identify and retrieve required information for a given work order to streamline the information access. The first step towards developing such a systematic approach is to understand how the required information to troubleshoot a given problem changes and what types of facility information HVAC mechanics need in general. I have conducted case studies with HVAC mechanics from three different facilities management organizations in the identification and validation phase. The research activities include shadowing work, interviews, and focus groups. In addition, literatures that related with HVAC system problems, causes, troubleshooting procedures, and information identification for FM have been reviewed. The research findings are validated in terms of the *generality* of the identified information requirements and characteristics of work orders that HVAC mechanics consider while troubleshooting of HVAC related problems.

RQ2: What representation schema and reasoning mechanisms enable identification of applicable causes and required information for a given work order?

The objective of this research question is to develop a formalized approach to reason about a building information model based facility information repository in order to automatically generate applicable causes for a given work order, and to retrieve required facility specific information. The developed reasoning mechanisms first uses BIM to detail a work order's context, which is composed of the characteristics identified in RQ1, and identifies generic set of applicable causes based on a matrix between the library of causes and work order contexts developed as part of this research. When retrieving the required information about an HVAC component, which is listed among the applicable causes, there is a challenge of finding corresponding components in the IFC file of the specific facility due to IFC's limitation in differentiating instances of HVAC components of the same type but perform different functions. I have established a set of constraints for different HVAC components that inherit from the design standards, which are used to differentiate the instances of HVAC components of the same type. The reasoning mechanisms further refine the set of causes based on the specific configuration of the HVAC system serving the reported space and retrieve relevant information. Moreover, a representation schema has been developed and used as the underlying data structures to pull the data from different sources together. The representation has been built upon IFC, and uses object-oriented modelling to extend IFC for the information item that is required by HVAC mechanics but not covered in latest IFC representation schema (IFC4). A prototype was implemented and the approach was validated for its *efficiency* and *accuracy* (in terms of *precision* and *recall*) of identifying applicable causes and retrieving required information for different work order contexts.

RQ3: How much the efficiency of the decision-making process during tasks of troubleshooting HVAC related problems can be improved by visualization?

As an earlier exploratory work, I evaluated the visualization techniques of displaying BAS data for facility monitoring tasks and found that that displaying the same information using different interfaces significantly affected users' efficiency of completing the same task. This research question builds on the hypothesis that visualization of the required information for HVAC mechanics can improve the efficiency of the decision-making for the troubleshooting process. However, there is a lack of understanding on how much the efficiency of the troubleshooting process can be improved by providing the information in visual forms. The objectives of this research question are (a) generate a classification of visualization techniques applicable for displaying the required information to troubleshoot HVAC related problems and get user-feedbacks about the visualization techniques, (b) implement an information visualization platform for HVAC mechanics based on the user-feedbacks, and (c) conducted further user studies to understand its impacts on HVAC mechanics' work efficiency of troubleshooting HVAC related problems.

Chapter 2. Characteristics of work orders and information requirements of HVAC mechanics to troubleshoot HVAC related problems

The motivating case study explained in section 1.1 showed that applicable information requirements for troubleshooting of HVAC related problems changed as characteristics of work orders change. Currently the identification and collection of required information for different work orders is conducted manually by HVAC mechanics, and as a result it is observed from the case study that even experienced HVAC mechanics wasted time when they were not familiar with the spaces and systems. In order to develop a systematic approach to provide information support for troubleshooting of HVAC related problems, the first and fundamental step is to understand what facility information HVAC mechanics need in general and how the required information to troubleshoot a given problem changes. This chapter describes the results of research done in identifying a set of information items that are required by HVAC mechanics when troubleshooting HVAC related problems, and the characteristics of work orders that change applicability of a given facility information to solve a reported problem.

2.1 Background research

The research presented in this chapter builds upon and extends previous work done in relation to HVAC maintenance. I grouped the related previous work in three categories: a) categorization of HVAC related problems, b) developing HVAC related troubleshooting procedures, and c) identification of facility information for facilities management.

2.1.1 Research studies done on categorization of HVAC related problems

There have been previous research studies that summarized common HVAC related problems (e.g., Hyvärinen & Kärki 1996; Marton 2012; Friedman 2004; Fletcher 1999b; Goins and Moezzi 2012). Categories of HVAC related problems that were identified in previous research studies include (a) temperature problem, such as "too hot/cold" (e.g., Marton 2012; Friedman 2004; Fletcher 1999b; Goins and Moezzi 2012), "room temperature deviation" (e.g., Hyvärinen & Kärki 1996); (b) air flow problem, such as "too much or little air volume" (e.g., Hyvärinen & Kärki 1996), "air movement too high/low" (e.g., Goins and Moezzi 2012), "stuffy or still air" (e.g., Fletcher 1999b), "draughts" (e.g., Fletcher 1999b, Marton 2012); (c) humidity problem, such as "humidity too high/low" (e.g., Goins and Moezzi 2012) and "dry eyes throat or skin" (e.g., Fletcher 1999b), (d) water leakage of HVAC systems (e.g., Hyvärinen & Kärki 1996), (e) abnormal noise or vibration of HVAC systems (e.g., Hyvärinen & Kärki 1996, Fletcher 1999b), and (f) poor air quality (e.g., Hyvärinen & Kärki 1996) such as odors (e.g., Fletcher 1999b). These studies constituted a point of departure for this research to enumerate the types of HVAC related problems. There are also indoor air quality (IAQ) related problems which can cause occupants' health related symptoms such as headache, fatigue, cough, lethargy, and shortness of breath (Burton 1993, 1994; Agle & Galbraith 1991; National Institute for Occupational Safety 1998), which are out of the scope of this research because the link of these problems with HVAC system is less clear and they are more likely to be caused by other factors (Fletcher 1999b).

2.1.2 Guidelines and research studies on providing HVAC related troubleshooting procedures

Manuals and guidelines are available for providing instructions to HVAC mechanics for troubleshooting of HVAC related problems (e.g., Fletcher 1999a and 1999b; Burton 1993 and

1994; Agle & Galbraith 1991; National Institute for Occupational Safety 1998) HVAC troubleshooting manuals (e.g., Fletcher 1999a and 1999b) aim to help HVAC mechanics to solve HVAC related problems. They provide step-by-step instructions and checklists to identify causes and solve HVAC related problems. In addition to the manuals, there are also guidelines (Burton 1993 and 1994; Agle & Galbraith 1991; National Institute for Occupational Safety 1998) provided for preventing and solving IAQ related problems. Though IAQ related problems have a wider scope than the focus in this study, the instructions included in the guidelines about the investigation of buildings, spaces and HVAC systems are also applicable for HVAC related problems. Similar to the HVAC troubleshooting manuals, these guidelines also provide rules of thumbs and general checklists to investigate IAQ related problems. There are also previous research studies that proposed strategies or practices for addressing HVAC related problems. Such studies either provided checklists for diagnosing specific types of problems, such as "too hot/cold" complaints (e.g., Friedman 2004) and thermal comfort related problems (e.g., Budaiwi 2007, Budaiwi et al. 2009) or provided strategies for troubleshooting of occupant discomfort for a specific facility as a case study(e.g., Terranova 1997). Besides providing a generic set of actions to diagnose HVAC related problems, these manuals, guidelines and research studies describe what information needs to be checked in the process, and thus they constitute a point of departure for this study to identify general information requirements for HVAC mechanics when working on troubleshooting HVAC related problems.

The information referred in these guidelines/manuals and papers during the troubleshooting process were documented and used as part of the point of departure for this research. A summary of the information mentioned in these guidelines/manuals and papers are provided in Table 4. As shown in Table 4, literature mentions a wide set of information when viewed collectively. The synthesis of the information mentioned in previous studies can be grouped in four categories: (1) Information related to reported problems, which describes the characteristics of the reported problems, such as type, spatial scope and time pattern of the reported problems; (2) Information related to HVAC systems, such as the layout of HVAC systems, the location, the control logic, and the capacity of HVAC components; (3) Information related to reported spaces, such as the functionality of rooms affected by reported problems, the number of occupants in reported spaces and the number of extra heat-generating equipment; and (4) Information related to maintenance history, such as complaints log and maintenance records.

An important note here is that since none of manuals, guidelines, or research studies focused on identifying information requirements for troubleshooting HVAC related problems, the information summarized in Table 4 was elicited by me from the descriptions given in the troubleshooting procedures as a set of parameters and thus are ill-defined. This ill-definition was observed in two ways. Either the expected information items were not defined, which leaves way for misinterpretations of HVAC mechanics or the information mentioned in these studies are vague and could be interpreted differently. For example, “complaints log” and “maintenance record of HVAC components” are not defined at a level where one can assign a value and could mean different information to different HVAC mechanics, such as the maintenance action performed, maintenance date, and so on. Similarly, “condition of HVAC system serving the complaint area” can be described with different set of enumerations. Further work needs to be done to better define and detail these information requirements.

2.1.3 Previous studies done on identification of facility information for facilities management (FM)

It is well understood that the information necessary to support FM activities are ill-defined, inaccurate and incomplete (Liu et al. 1994; Clayton et al. 1998; Song et al. 2002), and thus various research efforts have been conducted to formally identify what facility information should be stored for FM activities. Liu et al. (1994) and Clayton et al. (1998) conducted surveys with FM personnel in order to identify important information for FM. The identified information include design related information such as space plan and drawings, construction related information such as drawings associated with major renovations, and operation and maintenance information such as equipment specifications. The findings of these surveys actually represent information sources instead of detailed information items. Studies also looked at capturing facilities maintenance histories (e.g., Akinci 2004; Akcamete 2011; Ergen et al. 2007; Hammad and Motamedi 2007; Motawa and Almarshad 2013). These studies are pioneers in identifying information requirements for FM activities, however the information items identified are for general FM activities, are not identified for each FM task and also not necessarily specific and detailed enough for troubleshooting of HVAC related problems.

Recent research studies and data standardization efforts started to look into using information models to provide required information for FM activities. Different information models or databases were developed to store the required information (Lucas et al. 2013; Motamedi et al. 2014; Lee and Akin 2011). Examples of data standards that consider FM or HVAC domain's needs include Construction Operations Building Information Exchange (COBie), HVAC information exchange (HVACie), Automating Equipment Information eXchange (AEX), and Industry Foundation Classes (IFC). Again, none of these studies primarily focused on troubleshooting of HVAC related problems, but the information that they defined in relation to HVAC related maintenance was useful for this research. Examples include HVAC zones, HVAC system parameter values and setpoints, location, control logics and capacity of HVAC equipment. These information items are also summarized in Table 4.

Table 4. Summary of information requirements elicited from literature

	Information requirements	**Mentioned by literature**
	Reported problem related	
1	Type of problems	Burton (1993); Motamedi et al. (2014); Lucus et al. (2013)
2	Time pattern of problems	Agle and Galbraith (1991); Fletcher (1999b)
3	Spatial scope of problems (widespread, individual rooms, zones, or AHU systems)	Agle and Galbraith (1991); Fletcher (1999b); Terranova (1997)
	HVAC system related	
4	Type of HVAC systems (e.g., CAV or VAV)	Agle and Galbraith (1991); Burton (1993); Terranova (1997)
5	HVAC zones	Agle and Galbraith (1991); Friedman (2004); Lucus et al. (2013);
6	Layout of HVAC system serving the complaint area	Agle and Galbraith (1991); Burton (1993); Terranova (1997);
7	Location of HVAC equipment and components serving the complaint area	Agle and Galbraith (1991); Fletcher (1999b); Burton (1993); Motamedi et al. (2014)
8	Capacity of HVAC components or equipment serving the complaint reported area	Agle and Galbraith (1991); Friedman (2004); Terranova (1997); Motamedi et al. (2014)
9	Control sequence/logic of HVAC system serving the complaint reported area	Agle and Galbraith (1991); NIOSH (1998); Burton (1993); Terranova (1997)
10	Ventilation rate recommended by ASHRAE	Agle and Galbraith (1991)
11	Condition of HVAC system serving the complaint area	Agle and Galbraith (1991); Motamedi et al. (2014)
12	Operation schedule of equipment	Agle and Galbraith (1991); Fletcher (1999b); Burton (1993)
13	HVAC component or equipment operation statuses	Agle and Galbraith (1991); Friedman (2004) Motamedi et al. (2014)
14	Trend logs from building automation systems	Friedman (2004)
15	HVAC system parameter values	Agle and Galbraith (1991); Terranova

		(1997); Friedman (2004); Burton (1993); Motamedi et al. (2014)
16	Setpoint and range for HVAC equipment	NIOSH (1998); Terranova (1997)
	Space related	
17	Current indoor environment parameters measurements (e.g., temperature, humidity, pressure, CO2)	Agle and Galbraith (1991); Budaiwi (2007); Burton (1993); NIOSH (1998)
18	As-designed space usage type and changes over time	Agle and Galbraith (1991); NIOSH (1998)
19	As-designed number of occupants and changes over time	Budaiwi (2007)
20	Addition of heat-generating equipment in space (e.g., computer, printer, coffee maker, paper shredder, etc.)	Agle and Galbraith (1991); Budaiwi (2007); Fletcher (1999b); Terranova (1997)
21	Relocation of partitions in space	Agle and Galbraith (1991); Fletcher (1999b)
22	Building/space operation schedule	Fletcher (1999b); Burton (1993); Lucus et al. (2013)
23	Building code standards	Burton (1993)
	Maintenance history related	
24	History of complaints, complaints log	Agle and Galbraith (1991); NIOSH (1998); Budaiwi (2007); Burton (1993); Lucus et al. (2013)
25	PM record, maintenance schedule	Agle and Galbraith (1991); Burton (1993); Motamedi et al. (2014)
26	Causes and solutions to previously reported problems	Fletcher (1999b)
27	Maintenance records of HVAC components	NIOSH (1998); Fletcher (1999b); Motamedi et al. (2014)

When identified and combined together, the literature provide valuable points of departure to understand what facility and system specific information HVAC mechanics should check, however, no single study collectively provided the required information for troubleshooting of HVAC related indoor air problems. In addition to this, the information requirements identified from literature are ill-defined and needs further work to define their meanings.

2.2 Research method

Multiple sources of evidence, a triangulation approach widely used in social sciences as a qualitative research technique, have been used in this study to achieve the objective, which is to identify the characteristics of work orders that play key roles in defining what information is needed for a work order, and a generic set of information requirements that form the foundation for a systematic information support for troubleshooting of HVAC related problems. I have used qualitative research methods including shadowing, interviews, and focus groups. A total of twenty-eight HVAC mechanics participated in the research, as overviewed in Table 5, and came from three different and large campus FM organizations. Fifteen HVAC mechanics from FM group 1 participated in the identification phase, and eleven HVAC mechanics from FM group 2 and two HVAC mechanics from FM group 3 participated in the validation phase. Table 5 provides general information about the three FM groups and HVAC mechanics who participated in this study.

Table 5. General information about the FM groups and participants in the research studies

	Size of campus	Managed buildings	Participants job title and number*	Years of experience
FM group 1	147 acres	Academic and administrative buildings; Building ages from 1-105 years	10 HVAC mechanics	10 – 35 years
			2 Operation engineer leads	31 and 37 years
			3 BAS technicians	7, 10, and 35 years
FM group 2	132 acres		6 HVAC technicians	5 – 38 years
			1 BAS manager	24 years
			3 BAS technicians	15, 15 and 37 years
			1 Operation engineer lead	28 years
FM group 3	43 acres		1 HVAC supervisor	14 years
			1 Senior HVAC mechanic	24 years

*Note: The participants have different job titles, but they are all referred as HVAC mechanics in this thesis

The participants were involved in the study in different research tasks and the details of these tasks are provided below:

(1) Shadowing, direct observations and contextual inquiry: Shadowing is a research activity that allows researchers follow and observe the subject matter experts while they are performing their normal job activities, with the purpose to understand the current practices in a domain. Forty work orders were shadowed with HVAC mechanics from FM group 1 with follow up contextual inquiries when necessary. Contextual inquiry is a research method where conversions take place with subject matter experts under the context of their normal activities (Beyer and Holtzblatt 1998) in order to let them "think aloud" (Lewis 1982) so that their tacit knowledge can be captured. Through shadowing and contextual inquiry, the timed actions of HVAC mechanics as well as the information used in each step were captured in sequence. This research method was the most direct and accurate way of following the work order details and capturing information requirements for HVAC mechanics, but the collected data set is typically smaller than what is achieved through other methods since shadowing requires special permission and consent of the participants for being shadowed.

(2) Interviews: In order to reach out to more HVAC mechanics and getting a more general set of information requirements and work order characteristics, I also interviewed fifteen more HVAC mechanics from two different FM organizations (eight new participants in the identification phase and seven in validation phase). During the interviews, participants were asked to describe their typical working processes when responding to HVAC problem related work orders, what information they typically use in each process, what characteristics of the assigned work orders affect the information they would use, where they can get the required information, and any difficulties that they experience in getting the required information. Unlike the shadowing work,

which limits the findings to the characteristics of work orders at hand, interviews provided more work order cases, which were described by HVAC mechanics retrospectively, and included information requirements which could not be observed in the shadowed work orders.

(3) Focus groups: Focus group method is a formal research method to collect opinions of a group of experts (Merton and Kendall 1946) for a specific area. Focus groups include predefined discussion topics, and controlled environments where participants are encouraged to give their opinions and talk with each other around the defined topics (Krueger and Casey 2009). Focus group discussions are interactive in nature among different participants so that individual bias can be avoided (Morgan et al. 1998). I conducted four focus groups with fifteen HVAC mechanics (from FM group 1 in the identification phase), and two focus groups with eight HVAC mechanics (from FM group 2 in the validation phase). Each focus group included three to four participants. Similar questions were asked as that in individual interviews, but the difference was that in focus groups there were discussions and interactions among multiple HVAC mechanics and the resulting research findings were considered as the consensus of the participants in each focus group session.

(4) Exploration of current computerized systems used by HVAC mechanics and literature review: The existing computerized systems that HVAC mechanics usually use to get required information were also explored, in order to understand what information was available or provided to HVAC mechanics. The existing computerized systems that were examined include eight building automation systems (BAS) and around 430 work orders in a Computerized Maintenance Management System (CMMS). During shadowing work whenever HVAC mechanics used these systems, the information items that they used were recorded; and in interviews and focus groups, participants were asked what information they use from these

existing systems. The identified information items from other sources were also compared with what is provided in these systems.

The findings of information requirements identified from literature as documented in Table 4 were also incorporated. Though a portion of the information identified from literature was ill-defined or could have different meanings, the ones that were detailed at attribute level were compared and used as complementary to the findings identified in this research.

2.3 Research findings and validation

The research findings, obtained through the research tasks described in the previous section are twofold: a) the major characteristics of work orders that impact what information to consider during troubleshooting of HVAC problems and b) the information that should be readily available for HVAC mechanics in FM databases to provide a systematic information support for troubleshooting of HVAC related indoor air problems. The findings are detailed in the following subsections.

2.3.1 Characteristics of work orders

As presented in the motivating case study, the information requirements used for troubleshooting of an HVAC related work order change with the characteristics of work orders and there is need to identify the characteristics of work orders that affect the information requirements. The characteristics have been identified as (a) the *type of the reported problem*, (b) the *spatial scope of the reported problem, (c)* the *type of the HVAC systems, (d)* the *type of the control systems*, and *(e)* the *time pattern of the reported problem*. The definitions of these five characteristics and their enumeration values are provided in Table 6. The enumeration values for the type, spatial scope and time pattern of reported problems were identified both from the research tasks and the extensive literature review. The type of HVAC systems and control systems were defined in the ASHRAE handbook and used in this research (ASHRAE 2008, 2009).

Table 6. The identified characteristics of work orders and definitions

Characteristics of work orders	**Definitions**	**Enumeration values**
Type of reported problems	The nature of a problem that is sensed and reported in a work order by occupants	Temperature; Air flow; Humidity; Odor; Water leak; Noise
Spatial scope of reported problems	The multiplicity of the HVAC thermal zones or systems that serve affected spaces reported in a work order	Single zone in a multi-zone system; Multiple zones in a multi-zone system; Single zone/system in a single-zone system; Multiple systems
Type of HVAC systems	The type of HVAC system that serves a space reported in a work order	All-air single-duct VAV system; All-air single-duct CAV system; All-air dual-duct system; Air-water (FCU) system; Air-water (radiator) system; All-water (FCU) system; All-water (radiator) system
Type of control systems	The primary source of energy for the control of the HVAC systems	Pneumatic control; Electric control; Self-powered control
Time pattern of reported problems	The pattern in which the same problem in a space occurs repeatedly in a particular time range during a day	Morning (6am-12pm); Afternoon (12pm-6pm); Evening (6pm-12am); Night (12am-6am)

As explained in the motivating case study, *the type of reported problems* and *type of the HVAC system* for a given work order affect the possible causes and associated information that HVAC mechanics would consider. Similarly, because an HVAC system has hierarchies of components serving rooms in the entire systems or only specific zones, the *spatial scope of reported problems* affect the required information for HVAC components that exist in different parts of an

HVAC system. For example, if a temperature problem only happens in a single zone, the components in terminal systems such as reheat coil, reheat valve and zone damper need to be checked and the information associated with these components would be required. However, if the same temperature problem is reported for multiple zones, the components in the central air handling unit (AHU), such as cooling/heating coil and valves, would have a higher priority to check instead of components in terminal systems, and thus information related with these components would be required. *Type of control systems* determines whether information associated with auxiliary control devices is required, such as the operation status of air compressors for pneumatic control systems, and the voltage/current readings for signal transducers for electric type of control systems. *Time pattern of the reported problems* helps HVAC mechanics to find if there is a match with the pattern of the schedule of HVAC equipment. For example, if a noise problem always happens in the afternoon while a nearby AHU is scheduled to run in the afternoon, information associated with the AHU would be part of the applicable information. These five characteristics as a combination, with the corresponding values, define the context under which an HVAC related work order is generated.

The findings reported in Table 6 were analyzed in terms of at what phase of the research they were identified and how many times they were mentioned by the participants (i.e., the frequency of referrals). The frequencies of referrals of the identified characteristics in each evidence source are shown in Table 7. We can see from the table that the type of the reported problems, spatial scope of the reported problems, the type of HVAC systems, and the type of control systems were frequently used in different work orders and were unanimously agreed by all participants to be the characteristics they consider when defining what information to collect. Time pattern of reported problems was less frequently mentioned by participants.

Table 7. The evidence sources and frequency of referrals for the identified characteristics

	Characteristics of work orders	Identification phase			Validation phase	
		FM group 1			FM group 2 and 3	
		40 work orders	8 interviews	4 focus groups	7 interviews	2 focus groups
1	Type of reported problems	40/40	8/8	4/4	7/7	2/2
2	Spatial scope of reported problems	40/40	8/8	4/4	7/7	2/2
3	Type of HVAC systems	27/40	7/8	4/4	7/7	2/2
4	Type of control systems	33/40	3/8	4/4	7/7	2/2
5	Time pattern of reported problems	0/40	0/8	1/4	2/7	1/2

These five characteristics can be used to support identification of applicable causes and relevant information for HVAC mechanics to bring a more standard response to HVAC troubleshooting process- hence a more predictable distribution of work forces. The identification of generic set of information that will form the domain information for HVAC mechanics is presented in the next section.

2.3.2 Information requirements for troubleshooting HVAC related problems

Forty-two information requirements were identified through the research studies together with literature review and grouped into five categories. The categories and the information items in each category are: (1) HVAC related complaints log (including 6 information items), (2) HVAC system/component static information (including 10 information items), (3) HVAC system/component dynamic information (including 7 information items), (4) HVAC system/component historical information (including 7 information items), and (5) Space related information (including 12 information items). The identified information requirements are provided in Table 8 and explained in details as the following:

(1) HVAC related complaints log: This category of information depicts the history of HVAC related problems recorded in the same space over time and includes 6 information items as shown in Table 8. This information has been mentioned by literature as shown in Table 4, but lacks the definition of the detailed information items. Regardless of the context under which a new HVAC related work order is issued, HVAC mechanics would like to know the HVAC related complaints log reported in a given time period for a given space, in order to get insights from the complaint history and to see if there exist recurring problems. The findings from the cases studies showed that the information regarding each complaint should include *the type of the problem* (what happened), *date/time stamp* of the complaint (when it happened), *the cause* of the problem (why it happened, what failed or malfunctioned), *the remedial actions taken* (what was done) such as replace, repair and remove components, *responsible personnel* who worked on that work order (who solved it) and whether any *follow up actions* were needed. In the current practice, complaints log can be stored at and queried from Computerized Maintenance Management System (CMMS). It is found in this study that the list of historical complaints, time stamp and responsible person for the complaints are captured in the CMMS, but the exact causes, actions taken, and whether there is any follow-up action to be taken are not formally captured. In order to bring a formal and a systematic information support for HVAC troubleshooting process, such information should be collected and made readily available for HVAC mechanics.

(2) HVAC system/component static information: This category consists of information needed by HVAC mechanics that would reflect the static properties of HVAC systems and/or components. This set of information, which includes seven information items as shown in Table 8, is considered as static because it comes with the design of HVAC systems and is constant when the system is in operation. The static information can be related to individual HVAC components

(e.g., fan, coil, and damper) or to the entire HVAC system, and show differences for specific components or systems. This category of information is useful for HVAC mechanics to understand the design intents and features for HVAC systems/components and to find the right components they want to check.

HVAC component-specific static information needed during troubleshooting are the *location*, *control relationships* and *capacity* of the applicable components for the given problem. Applicable components refer to the HVAC components that are among the possible causes for a given work order. It was identified that the *location* information of HVAC components has two levels, i.e., the space ID where an applicable component is located at, and the x,y,z coordinates of an applicable component in that space, depending on the visibility of the components. CMMS can provide limited location information (i.e., space ID) of HVAC equipment as assets, but does not detail it for specific HVAC components. The location of an HVAC component can be found from well-detailed mechanical drawings, or through visual tracing on the field. HVAC mechanics also would like to know the *control relationships* among HVAC components defined during design for the control of the system, such as a thermostat *controls* a reheat valve, or a VAV damper *is controlled* by a thermostat. The information is usually documented in design documents of HVAC system specifications or new versions of BASs. *Capacity* of HVAC components/equipment serving the reported area is useful for HVAC mechanics to determine if the HVAC component/equipment is oversized or undersized to satisfy the needs of the served area. This information can be found from design documents of HVAC system specifications.

The static information about HVAC systems includes six items, as *the HVAC zones a system serves*, *whether an AHU uses 100% supply/return air*, the *type of hydronic systems*, *the brand name of applicable building automation system,* and *ventilation rate recommended by ASHRAE*.

An *HVAC zone* refers to a space/room or a group of spaces/rooms that are controlled by a single thermostat [41]. This information is essential in defining the spatial scopes of reported problems. *Whether an AHU uses 100% outside or return air* was identified as an important piece of information for HVAC mechanics while troubleshooting humidity problems in order to get a sense of how much indoor spaces are affected by outdoor ambient conditions. *Types of hydronic systems*, such as domestic water, drain, chilled water, and hot water systems, are necessary to know for differentiating leakage types. In addition, for DDC type of control systems, it is necessary for HVAC mechanics to know the *brand name of applicable building automation system* so that they will know which building automation system to login to check HVAC dynamic information for a given work order. This information is especially needed when the building is served by multiple BAS products and HVAC mechanics need to know which system serves which area so that they can find the right one to check. Lastly, the *ventilation rate recommended by ASHRAE* is mentioned by literature as required for HVAC mechanics to understand the design intents.

(3) HVAC system/component dynamic information: This category includes the information that changes when the system is in operation, which is required for HVAC mechanics to understand the current statuses and performances of HVAC systems. The information is mainly generated in a BAS and includes eight items: the *current values of measured parameter, setpoints of controlled parameters, control commands of applicable HVAC components, the feedback signal of control commands, the component/equipment control mode, the trend logs, the operation mode of HVAC equipment, and the usage condition of fume hoods* as shown in Table 8. Many parameters such as supply air flow rate, supply air static pressure, mixed air temperature are controlled in HVAC systems and they reflect the performance of an HVAC system at a given

point in time. These parameters usually have *setpoints*, reflecting the ideal or aimed values, and *current values* are measured by corresponding sensors at regular frequencies set by control engineers. *Control commands* refer to operational status signals that are sent by BASs to the controlled devices, which apply to the controlled devices include fan, damper and valve, such as the speed percentage of a fan, the opening percentage for a damper/valve. Control commands have corresponding *feedback signals*, which measure the actual operation statuses of the controlled devices. Automatic control commands can be overwritten by manual control commands by setting up the controlled devices at specific positions. Manual control mode is necessary when automation system is malfunctioning, or equipment is in maintenance. The parameters and control signals can be recorded and put in a time-series chart by BAS as *trend logs*, which are helpful for HVAC mechanics to know the historical changes and trends in parameters. The required information also includes the *operation mode* of applicable HVAC equipment, such as an AHU, a chiller and a boiler is in operation mode or shutdown mode. In addition, the usage condition of fume foods (i.e., in use or in idle) is used when air flow problems happen in exhaust systems serving fume hoods. This category of information can be obtained from BAS for HVAC systems that use direct digital control (DDC), or have to be manually checked at the field for HVAC systems that use pneumatic control.

(4) HVAC system/component historical information: This category of information contains the maintenance history related with applicable HVAC components and commissioning history with HVAC systems. This category of information is helpful for HVAC mechanics to identify what components could be the reason for the problem and prioritize these components for their order of checking. I have identified seven information items in this category as shown in Table 8. *Failure frequencies* of applicable HVAC components define the number of failures that occurred

for a component in a selected time frame. It was observed that if an HVAC mechanic knew that a component had high failure frequencies in previous work orders, they would start checking that component first. HVAC mechanics also want to know the history of the previous work orders associated with components identified as applicable causes for a given work order. More specifically, for each work order identified in a given time period for a given HVAC component, history would constitute *the date/time stamp of previous maintenance*, *the responsible personnel*, *the type of maintenance* [i.e., Preventive Maintenance (PM) or Corrective Maintenance (CM)]; if a work order is a CM work, *what were the problem types associated with the given components* and *what remedial actions were taken* to address these problems. This set of maintenance history information is similar as that of complaints log, but the difference is that complaints log is associated with the spaces, while component maintenance history is associated with specific HVAC components. Besides, if a system has been recently installed or remodeled, *whether the new system has been commissioned or not* is defined as a useful information item to know during troubleshooting.

(5) Space related information: There are also information items related with the spaces that are reported in work orders and I have identified twelve of such information items as shown in Table 8. *Occupancy schedule of spaces*, which represents the time frames that a space is scheduled to be used for certain activities or is idle. It is helpful for HVAC mechanics to plan the time for field inspection. It is also required if there is any pattern in the time of reported problems (e.g., whether the problem is observed always in morning times or at night). For example, if a classroom is always reported to be too hot when there is class going on in the morning, then this information is used to check the designed capacity of HVAC system with respect to the current number of occupants to determine sufficiency of the HVAC system for conditioning that space.

Access type to a reported space, which defines whether there is restricted access to a space or not, and the *name of personnel with access to the reported space* are required when the reported spaces have access restriction for maintenance personnel. *Indoor environment parameter (IEQ) requirements,* such as temperature, humidity, and air pressure requirements for the spaces are necessary for HVAC mechanics to understand the design intent for the reported space. Furthermore, the changes of space properties that affect the heating/cooling load and air distribution would cause HVAC related problems too, and hence the as-designed and as-is values of these properties are required. These include the *usage type of a space*, *the number of occupants*, *the number of heat-generating equipment in that space*, and the *layout of interior walls/partitions*.

Table 8 shows the above described list of findings in categories. It will be important to note that, the *HVAC related complaints log* are required for each work order, while the *HVAC component static information*, *dynamic information*, *historical information*, and *space related information* are needed per cause identified as applicable and should be checked for a troubleshooting case. An applicable cause for a reported problem can be an HVAC component or a space specific factor (e.g., change in as-designed number of occupants). For example, if a thermostat, a reheat valve, and a VAV damper are among the applicable causes for a reported problem, static information, dynamic information and historical information only for these components will be needed during the troubleshooting process and similar set of information for the rest of the components will not be needed.

Table 8. Identified information requirements, categories and their frequency of referraals during each method of identification

	Information requirements	Identification phase			Validation phase		Literature	Existing systems
		FM group 1			FM group 2 and 3			
		40 work orders	8 interviews	4 focus groups	7 interviews	2 focus groups		
	HVAC related complaints log						✓	
1	*HVAC related problems reported for a given period in the same space*	3/40	*4/8*	*4/4*	*7/7*	*2/2*	✓	***CMMS***
2	*Date/time stamp of historical complaints*	3/40	*4/8*	*4/4*	*6/7*	*2/2*		***CMMS***
3	*Causes of historical complaints*	3/40	*4/8*	*4/4*	*7/7*	*2/2*	✓	
4	*Remedial actions taken for historical complaints*	3/40	*4/8*	*4/4*	*7/7*	*2/2*	✓	
5	*Name of responsible personnel*	0/40	*3/8*	*4/4*	*6/7*	*2/2*		***CMMS***
6	Need for any follow-up actions	0/40	3/8	2/4	2/7	1/2		
	HVAC system and component static information							
7	***Location of applicable HVAC components***	***38/40***	***8/8***	***4/4***	***7/7***	***2/2***	✓	***CMMS-Limited****
8	***Control relationships of applicable HVAC components***	***28/40***	***8/8***	***4/4***	***7/7***	***2/2***	✓	***BAS-Limited****
9	***HVAC zones a system serves***	***25/40***	***8/8***	***4/4***	***7/7***	***2/2***	✓	
10	Whether an AHU uses 100% outside air	1/40	2/8	1/4	3/7	1/2		
11	Whether an AHU uses 100% return air	0/40	1/8	0/4	2/7	0/2		
12	Type of hydronic systems (e.g., domestic water, drain, chilled water)	2/40	0/8	1/4	2/7	0/2		
13	*Brand name for applicable BASs*	*9/40*	*8/8*	*3/4*	3/7	0/2		
14	Capacity of HVAC components or equipment serving a reported space	0/40	0/8	0/4	0/7	0/2	✓	
15	Ventilation rate recommended by ASHRAE	0/40	0/8	0/4	0/7	0/2	✓	
	HVAC system and component dynamic information							
16	***Current values of measured parameters (e.g., temperature, flow rate, pressure)***	***30/40***	***8/8***	***4/4***	***7/7***	***2/2***	✓	***BAS***
17	***Setpoints of controlled parameters***	***19/40***	***8/8***	***4/4***	***7/7***	***2/2***	✓	***BAS***
18	***Control commands of applicable HVAC***	***27/40***	***8/8***	***4/4***	***7/7***	***2/2***	✓	***BAS***

	components (e.g., % of opening, % of speed)							
19	Control command feedback signal of applicable HVAC components (e.g., % of opening, % of speed)	0/40	0/40	0/40	2/7	1/2		***BAS***
20	*Equipment control mode (i.e., manual or automatic)*	0/40	1/8	1/4	*4/7*	0/2		***BAS***
21	*Trend logs of measured parameters or control commands*	1/40	1/8	0/4	3/7	1/2	✓	***BAS***
22	*HVAC equipment operation mode (i.e., in operation or shutdown)*	8/40	3/8	2/4	*6/7*	1/2	✓	***BAS***
23	Fume hood usage condition (i.e., in use or in idle)	1/40	0/8	0/4	1/7	0/2		
	HVAC system and component historical information						✓	
24	Failure frequencies of applicable HVAC components	5/40	0/8	1/4	3/7	0/2		
25	*Previous problem types reported for applicable HVAC components*	5/40	3/8	*4/4*	*7/7*	*2/2*		
26	*Remedial actions taken for each previous problem for applicable HVAC components*	5/40	3/8	*4/4*	*7/7*	*2/2*		
27	*Date/time stamp of previous maintenances of applicable HVAC components*	5/40	3/8	*4/4*	*6/7*	*2/2*		
28	*Maintenance type (i.e., CM or PM)*	5/40	3/8	*4/4*	*7/7*	*2/2*		
29	*Name of responsible personnel for previous maintenances*	5/40	3/8	*4/4*	*7/7*	*2/2*		
30	Whether a new system has been commissioned or not	0/40	0/8	2/4	2/7	1/2		
	Space related information							
31	Occupancy schedule of a reported space	1/40	0/8	0/4	3/7	0/2	✓	
32	*IEQ requirements for a reported space*	3/40	3/8	2/4	*4/7*	1/2	✓	
33	Access type to a reported space (i.e., access restriction or not)	1/40	3/8	1/4	3/7	0/2		
34	Name of personnel with access to a reported space	1/40	3/8	1/4	3/7	0/2		
35	*As-designed usage type of a reported space*	3/40	*5/8*	*4/4*	*7/7*	*2/2*	✓	

36	*As-is usage type of a reported space*	3/40	*5/8*	*4/4*	*7/7*	*2/2*	✓	
37	*As-designed number of occupants for a reported space*	0/40	1/8	2/4	*6/7*	*2/2*	✓	
38	*As-is number of occupants for a reported space*	0/40	1/8	2/4	*6/7*	*2/2*	✓	
39	*As-designed number of heat-generating equipment in a reported space*	0/40	1/8	*4/4*	*7/7*	2/2	✓	
40	*As-is number of heat-generating equipment in a space*	0/40	1/8	*4/4*	*7/7*	2/2	✓	
41	As-designed layout of interior walls/partitions for a space	0/40	0/8	2/4	4/7	0/2	✓	
42	As-is layout of interior walls/partitions for a space	0/40	0/8	2/4	4/7	0/2	✓	

Note: ***Bold and Italic***: high frequency of referral; *Italic*: medium frequency of referral; normal: low frequency of referral

*CMMS-limited: location information is only provided as space ID for HVAC equipment asset instead of component.

*BAS-limited: out of the eight BASs reviewed in this study, only one BAS has the functionality to show control relationships.

A frequency of referral analysis has been performed to better understand the distribution of information items with respect to the research tasks used to identify them. This analysis is needed to highlight the information items that were highly referred regardless of the research tasks and to prioritize them as a step towards formal information support for troubleshooting process. The frequencies of referrals are shown in Table 8 and represent the number of work orders where a given information item was used, the number of participants who referred to a given information item, and the number of focus group sessions that stated the importance of that item in shadowing, interviews and focus group sessions, respectively. In this study, the referral rates were categorized into three as: (a) high frequency, when the referral rate was greater than 50% in all means of identification (i.e., research tasks) and is written in ***Bold and Italic*** in Table 8; (b) medium frequency, when the referral rate was greater than 50% in at least one research task and is written in *Italic* in Table 8; and (c) low frequency, when the referral rate was less than 50% in all research methods and is written in normal font in Table 8.

As shown in Table 8, the highly referred information items that were identified as useful during troubleshooting process include location and control relationships of applicable HVAC components, HVAC zones a system serves, current values and setpoints of controlled parameters, and control commands of applicable HVAC components. These information items had high referral rates in all methods of identification since they are needed for HVAC related problems for almost all work orders, and also they are relatively easier to get from existing data sources such as CMMS, BAS, design documents, or through field inspection. These information items are also referred in literature as shown in Table 8.

The information items categorized as medium frequency were all frequently referred in interviews and focus groups, but were not observed to be frequently used in shadowed work orders. We can see that half of these information items belong to the category of complaints log and HVAC components historical information, including previous HVAC related complaints (i.e., types of the problems) reported for a given period in the same space, date/time stamp, causes, remedial actions, name of responsible personnel of historical complaints, previous maintenance date/time stamp of applicable HVAC components, previous types of problems, name of responsible personnel for previous maintenance, maintenance type, and remedial actions for the applicable components. This set of information is ill-defined in literature when the information is referred as "complaints log", "history of complaints", "maintenance schedule", and "maintenance records of HVAC components". Interviews and discussions in focus groups revealed the fact that though maintenance history related information is considered as very important by HVAC mechanics, in the current practice this set of information is not captured and stored completely in formal ways. Complaints log can be queried from CMMS, but only historical problems, date/time stamp and responsible personnel are captured, while the specific causes and remedial actions taken are not. Moreover, historical information about HVAC components is not available because the maintenance history is not captured at component level. This uncaptured information is collected as HVAC mechanics' tacit knowledge and experience. Our studies showed that an HVAC mechanic can be assigned with more than one hundred work orders a month in multiple buildings. It is very difficult for them to keep track of the historical information for each space and HVAC system in their mind, hence historical information was not observed to be used very often in the shadowing work.

In addition, *the brand name for applicable BAS* was also not frequently used in the shadowed work orders, because this information is only applicable when the type of control system is DDC and HVAC mechanics need to know which BAS to login. This reflects the fact that most of the shadowed work orders were associated with pneumatic controlled HVAC systems, since the buildings involved in the motivating case study are old buildings which mostly use old fashion control systems. The *brand name for applicable BAS* was frequently mentioned by participants from FM group 1, while not frequently referred by participants from FM group 2. The reason is that the FM groups use different strategies of selecting BAS manufacturers. Buildings in FM group 1 have products from multiple BAS manufacturers, while almost all building in FM group 2 use products from the same manufacturer. Hence, HVAC mechanics in FM group 1 needed to know the specific BAS manufacturers among different possible ones, while FM group 2 rarely needed that information.

With respect to the space related information, as-designed and as-is usage type, number of occupants, and number of heat-generating equipment in a reported space were observed to be frequently mentioned by participants both in interviews and focus groups, and also mentioned by literature, but not frequently used in shadowed work orders. The incidents of changes to space usage type, changes to occupants number and addition/removal of office equipment do not happen very often, but is considered by HVAC mechanics as important information to know when the changes happen to understand the sufficiency of HVAC equipment to the reported spaces and whether the reported problem is due to this insufficiency.

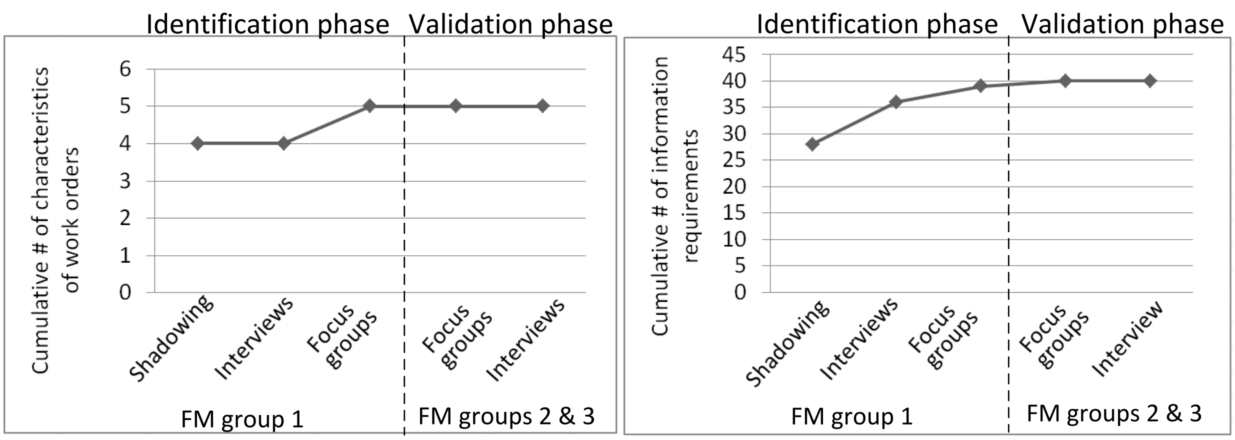
The rest of the requirements listed in Table 8 were observed to have low frequency of referral. This set of information can be considered as information that is only required by few HVAC mechanics and used in troubleshooting of few work orders, but not generally required. The reason for this was that these information items were needed in specific scenarios that are not generally applicable to various HVAC related problems. For example, “the type of hydronic systems” is only required when a water leakage problem is reported, “the access type to a reported space", and "the name of the personnel with access to a reported space" are only needed when the reported space area has access control for HVAC mechanics.

2.3.3 Validation of findings

The research findings are validated in terms of the *generality* of the characteristics of work orders that define the context of a work order and the identified information requirements of HVAC mechanics while troubleshooting HVAC related problems. The validation approaches used include triangulation for identification and external validation. Triangulation approach is to verify and compare the research findings from more than two sources (Campbell and Fiske 1959). In this study, I have used three different research tasks (i.e., interviews, shadowing, focus group sessions) and two investigation tasks (i.e., literature review and related computerized system examination).

External validation is used to evaluate the representativeness of the identified work order characteristics that affect what the information is used in the troubleshooting process and information requirements for HVAC mechanics when they work under different contexts (i.e., in different buildings, with different HVAC systems and under different FM practices). Hence I worked with twenty-eight experienced HVAC mechanics from three FM groups, and each of the FM group manages more than one-hundred buildings in their campuses with in-house FM groups. The participants brought experience from various buildings they work, from legacy buildings with more than one-hundred years' history with old generations of HVAC systems with pneumatic control, to modern buildings that became operational in recent years with highly sensed HVAC systems with DDC control.

Figure 4 (a) and (b) shows the cumulative number of identified characteristics of work orders and information requirements when additional research activities were conducted. The x-axis shows the research activities in chronological order, and y-axis is the cumulative number of identified characteristics of work orders and information requirements. We can see from the chart that with research activities progressing, fewer and fewer new characteristics and information requirements were identified. In Figure 4(a), at the point when focus groups were completed with FM group 1, and in Figure 4(b) at the point when focus groups were completed with FM group 2, the lines reached a plateau and no new characteristic of work orders or information item was identified.



(a) Cumulative number of characteristics of work orders identified in research tasks

(b) Cumulative number of information requirements identified in research tasks

Note: Shadowing/interviews/focus groups with FM group 1 represent the research activities done in the identification phase; Interviews/focus groups with FM group 2 and 3 represent the research activities done in the validation phase.

Figure 4. Cumulative number of characteristics of work orders and information requirements identified in research tasks

Validation findings are provided in Table 7 and Table 8. During the external validation with FM group 2 and 3, the identified characteristics of work orders are consistent with that identified in

FM group 1. Among 42 identified information items, 39 of them were identified with FM group 1 (non-zero frequency in Table 8), 40 were identified with FM groups 2 and 3, and 2 items were only identified from literature. The two information items that were only identified from literature include *capacity of HVAC component/equipment serving a reported space* and *ventilation rate recommended by ASHRAE,* which were mentioned by literature to be used to verify if the existing HVAC system configuration matches the requirements of served spaces, i.e., heating/cooling load and ventilation requirements. These two information items are more likely to be used by mechanical engineers or building commissioning experts, instead of HVAC mechanics for troubleshooting tasks at a daily basis, since engineering calculations are needed to obtain the space requirements. Additional one information item that was identified with FM group 2 and 3, but not with FM group 1 is the *control command feedback signal*. The reason is that the building automation systems used in FM group 2 and 3 have a better functionality of providing feedback signals for the control commands, which was not the case for FM group 1. The ratio of missed information items with FM group 1 in relation to all identified information items (3/42), and the ratio of missed information items with FM group 2 and 3 in relation to all identified information items (2/42) are all quite low. Therefore, we can conclude that the identified information requirements are generic for troubleshooting of HVAC related problems.

2.4 Conclusion

The research highlighted the challenges in the current practice that the information requirements for different work orders change with the characteristics, and in such circumstances even experienced HVAC mechanics miss key information and as a result waste time on non-value added troubleshooting steps. Five characteristics of work orders were identified and they define the context of a reported work order: (1) type of reported problems; (2) spatial scope of reported problems; (3) type of HVAC systems; (4) type of control systems; and (5) time pattern of reported problems. Moreover, 42 information items were identified collectively and grouped into five categories: (1) HVAC related complaint logs; (2) HVAC system/component static information; (3) HVAC system/component dynamic information; (4) HVAC system/component historical information; and (5) space related information. Among the 42 information requirements, 14% (6/42) of them had high referral rate regardless of the research method used to identify the information items. This means that this set of information is generally important for HVAC mechanics to know in different work orders. 50% (21/42) of the identified requirements has medium referral rate, which contains the information items that HVAC mechanics consider as important but are not frequently used in the current practice due to accessibility to such information in the current practice, such as complaints log and maintenance history of HVAC components, and the information items that are related with the causes of changes in space properties, which do not happen very often. These information items are valuable to know but either cannot be accessed since they are not collected in the current practice at the level of detail needed, or they are related to space related changes, which do not happen on a daily basis in buildings. 36% (15/42) of the identified requirements are neither frequently referred by HVAC mechanics, nor used in different work orders. These set of requirements are categorized as low frequency of referral, which were only required by few HVAC mechanics and used in troubleshooting of few work orders in our study. These information items were needed in specific scenarios that are not generally applicable to various types of HVAC related problems. The research findings were validated in term of the generality of the findings through triangulation validation and external validation.

The identified information requirements are helpful for FM organizations to bring more systematic information support for CM practices of HVAC related problems and can be used as a list of information items to store and use in FM databases for improving their maintenance practices and reduction of waste. The findings can also be used by researchers to develop a formalism to use the work order context for enabling identification of applicable causes and required information items for HVAC mechanics for reported problems to better plan the CM workforce.

Chapter 3. A model-based and automated approach to enable identification of applicable causes and retrieval of required information for HVAC related problems

Troubleshooting HVAC related problems is recognized as a challenging work because many possible causes could result in the same symptom for the reported problem (Fletcher 1999b; Budaiwi 2007), and various facility specific information needs to be collected as evidence to diagnose the real cause (Burton 1993). In the current practice, HVAC mechanics usually have to make decisions with limited understanding of the problems and insufficient information support (Gallaher et al., 2004; Gnerre et al. 2007), which could cause the delay of responses and the neglect of root cause (Goins and Moezzi 2012).

The study presented in Chapter 2 shows that applicable causes and relevant information to check for a reported problem change with the work order context, i.e., with the type of reported problem (e.g., a temperature vs. a humidity problem), the spatial scope of reported problem (e.g., problem being reported for a single zone vs. an multiple zones), the type of the HVAC system (e.g., a VAV vs. CAV system), and the control system type (e.g., pneumatic vs. electric), and the time pattern of the reported problem (e.g., always in mornings or afternoons). It is very challenging for HVAC mechanics to promptly identify complete set of applicable causes and keep track of the data sources generated for different buildings. Even experienced HVAC mechanics waste time on non-value added steps due to lack of information support. Therefore, there is a need for a systematic approach that would help HVAC mechanics to consistently pinpoint the right set of causes at the field and provide the required information about these causes promptly. The approach addresses two research challenges: (1) the need to provide customized set of causes for a given HVAC related problem, in order to reduce the search space and the possibility of neglecting root causes for HVAC mechanics; and (2) the need to provide required information for the reported problem, so that HVAC mechanics don't have to waste time on manually collecting required information from different sources.

This chapter provides the details of a formal approach that utilizes a model-based information repository to automatically identify applicable causes and retrieve relevant information for a given HVAC related problem in a facility. The approach extends the existing body of knowledge in using BIM for FM tasks with focus on troubleshooting of HVAC related problems.

3.1 Background research

The research study presented in this paper builds upon previous work done in the areas of guidelines on HVAC system configurations and troubleshooting of HVAC related problems, computerized approaches of FDD for HVAC systems, computerized approaches that use BIM for facilities maintenance, and information representation for FM.

3.1.1 Guidelines on troubleshooting of HVAC related problems

Various standards, handbooks and manuals are available for HVAC systems (e.g., ASHRAE Standard 180-2008; ASHRAE 2008, 2009; Agle and Galbraith 1991; Fletcher 1999a, 1999b; Burton 1993; Kreider 2001; Pita 1998; McDowall 2006). Within the scope of this research, the ones describing HVAC system types, components, and configurations, and the ones related with HVAC troubleshooting practices were studied in details.

The type of guidelines/manuals which provide detailed descriptions about HVAC system types, components, and configurations includes ASHRAE handbook – HVAC Systems and Equipment

(ASHRAE 2008), ASHRAE Learning Institute's Fundamentals of HVAC systems (McDowall 2006), Handbook of heating, ventilation, and air conditioning (Kreider 2001), and Air Conditioning Principles and Systems (Pita 1998). These guidelines/manuals provide resources for this study to enumerate the types of HVAC systems, list the components that constitute different types of systems, and understand the design constraints for different types of components.

Another type of guidelines/manuals are on HVAC troubleshooting practices, and the ones that were examined in details in this study include HVAC Troubleshooting Manual (Fletcher 1999a, 1999b), IAQ (Indoor air quality) and HVAC Workbook (Burton 1993), and Building Air Quality - A Guide for Building Owners and Facility Managers (Agle and Galbraith 1991). These manuals and guidelines provide instructions about the recommended workflows, rules of thumbs and generic checklists that can be useful for the troubleshooting procedures. In addition to these, there are similar research studies in the literature about strategies for investigation of HVAC related problems (e.g., Budaiwi 2007; Budaiwi et al. 2009) and management of HVAC system maintenance (e.g., Au-Yong et al. 2014). What these manuals, guidelines, and research studies have in common is that they constitute a good set of guiding materials for HVAC mechanics who may lack the technical background to troubleshoot HVAC related problems. A common problem with these guidelines, however, is that they do not consider the specific context under which work orders are generated (i.e., the specific HVAC systems and spaces in a facility), and thus would make the usability of such solutions to problems reported in specific contexts less effective due to either inapplicability of the steps provided in the guidelines to a given context or the lack of specific steps that would be needed for that context. For example, for the troubleshooting procedures provided in Fletcher (1999b), "check if the fire damper is closed" is one of the actions steps to troubleshoot a "too hot" problem (Fletcher 1999b), but not all HVAC systems have fire dampers and HVAC mechanics would waste time if they try to find a fire damper in HVAC systems that do not have such dampers; on the other hand, reheat valve is a possible cause for a "too hot" problem, but it is not included in the checklist, which will cause the neglect of a possible cause. Furthermore, even though these manuals, guidelines and research studies also describe what information that HVAC mechanics should collect in the troubleshooting process, it still requires much manual work to search through various data sources and inspect the specific systems/spaces to collect the required information.

3.1.2 Computerized approaches for FDD for HVAC systems

Many computerized approaches have been developed for identifying faults in HVAC systems, such as automatic fault detection and diagnosis (FDD) and automatic commissioning (e.g., Chen and Braun 2000; Xu and Haves 2002; Xiao 2004; Choi et al. 2004; Qin and Wang 2005; Schein and Bushby 2005; Sallans et al. 2006; Schein et al. 2006; Djuric et al. 2008; Holcomb et al. 2009). Automatic HVAC FDD and commissioning approaches can be grouped under three main categories: quantitative model-based, qualitative model-based and data-driven (Katipamula and Brambley 2005). These approaches also differ in terms of their scope (i.e., the targeted faults) to detect and diagnose in different HVAC components or subsystems. For example, there exist research studies that focus on fault detection solely on sensors (e.g., Xiao 2004; Sallans et al. 2006), variable air volume boxes (e.g., Qin and Wang 2005), air handling units (e.g., Schein et al. 2006), chiller plants (e.g., Choi et al. 2004), chilled and hot water pumps (e.g., Holcomb et al. 2009), rooftop units (e.g., Chen and Braun 2000), mixing box and fan systems (e.g., Xu and Haves 2002), hydronic heating systems (e.g., Djuric et al. 2008), or a combination of these subsystems (e.g., Schein and Bushby 2005), hence limiting the usability of FDDs to collectively detect various possible causes in a given HVAC system.

Even though such a large amount of automated FDD and commissioning approaches exists, troubleshooting HVAC related problems is still an indispensable part of maintenance practice for various reasons. First, these FDD and commissioning approaches all have their weaknesses and limitations (Katipamula and Brambley 2005; Dash et al. 2000), such as it is almost impossible to develop a complete set of rules that are applicable for all HVAC systems for qualitative-model based approaches, or to develop an accurate mathematical model for quantitative-model based approaches, or to satisfy the need for large historical datasets in order to train a model for data-driven approaches. Also, FDD approaches generally need readings from sensing and metering devices, control signals and the status of controlled equipment in HVAC systems. It would not be a problem of getting access to this information for systems with Direct Digital Control (DDC) type of control. However, the existing old buildings use pneumatic systems and will not be able to provide this input. In pneumatic systems, HVAC operational data has to be measured manually on field, which adds more difficulties of applying automatic FDD approaches. Finally, automatic FDD or commissioning approaches are generally designed to identify HVAC system faults, i.e., malfunctioning HVAC components, but various other factors, such as space function alternations, space physical layout changes, any decrease/increase in the number of heat-generating equipment in spaces (Budaiwi 2007) could also cause HVAC related problems. Due to these limitations in applying automatic FDD in practice, HVAC mechanics' investigation and troubleshooting is still necessary for corrective maintenance. Hence, the research presented in this paper benefits from studies in this category in terms of the information represented in such approaches but differ in scope by focusing on the corrective maintenance through troubleshooting.

3.1.3 Computerized approaches that utilize BIM for facilities maintenance

It is a known issue in the FM industry that the lack of information support has caused significant resource waste (i.e., around $1.5 billion) because facility maintenance staff has to stay idle waiting for information or spend extra time for looking for facility information (Gallaher et al. 2004). Building Information Models (BIM) have been used to facilitate the information exchange through the lifecycle of a building, including the facilities management phase. The related research studies can be described under two categories: the studies that looked at the development of BIM-based frameworks, and the reasoning approaches developed to capture, store or retrieve facility information using BIM.

Most of the previous research studies that focus on using BIM for facilities maintenance proposed various BIM-based frameworks to streamline existing processes (e.g., Ammari and Hammad 2014; Lin and Su 2013; Chen et al. 2013; Shen et al. 2012; Lin et al. 2012; Lee and Akin 2001). Within the scope of this paper, maintenance related research studies have been examined and discussed as they overlap with the scope of the research presented in this paper. Examples of such studies include the BIM-based facility maintenance management (BIMFMM) system (Lin and Su 2013), agent-based service-oriented system to integrate facility maintenance management, BIM and RFID based asset tracking system (Shen et al. 2012), 2D barcode/BIM-based facility management (2DBIMFM) system (Lin et al. 2012), 3D-based facility maintenance and management system (Chen et al. 2013), BIM-based markerless mixed Reality system (Ammari and Hammad 2014), and augmented reality-based operation and maintenance (AR-based O&M) fieldwork facilitator (Lee and Akin 2001). Such studies either focused on facilities management as a whole without differentiating the subsystems to be analyzed (e.g., Ammari and Hammad 2014; Lin and Su 2013; Chen et al. 2013; Lin et al. 2012; Shen et al. 2012) or further focused on multiple building subsystems (e.g., Lee and Akin 2001). These studies showed the value of using BIM and efficiency that can be obtained using model-based information repositories. However, such studies have not focused on troubleshooting of HVAC related problems, and hence showed differences with the research presented in this paper that focuses on identification of applicable causes and information requirements for troubleshooting of HVAC related problems. In addition, these studies mostly describe the enabling technologies and system architecture to incorporate BIM into the decision-support systems for the facility maintenance management practices, but no reasoning mechanisms have been developed to provide information for specific tasks.

Another category of BIM for FM related studies that are relevant with this study included developing reasoning mechanisms to capture, store or retrieve information using BIM for facilities maintenance (e.g., Akcamete 2011; Motawa and Almarshad 2013; Lucas et al. 2012; Motamedi et al. 2014;). Examples included using BIM to generate customized templates for capturing maintenance work related changes in the facilities (Akcamete 2011), and using case-based reasoning (e.g., Motawa and Almarshad 2013) and fault-tree analysis (e.g., Lucas et al. 2012; Motamedi et al. 2014) to reason with the stored information and provide information support for facility maintenance tasks. These studies have the same scope as the study presented in this paper in terms of developing automated approaches to customize generated information for a specific maintenance task, hence are complementary to the research presented in this paper.

These studies differ from the presented research in terms of the scope, which is on HVAC related troubleshooting.

3.1.4 Information representation for FM

An information model or a representation schema describes concepts, relationships, rules, constraints, and operations in a domain (Lee 1999). There have been many efforts on developing information models for FM and HVAC domain (e.g., IFC, COBie, HVACie, AEX, Wix et al. 1999; Yu et al. 2000; Hassanain et al. 2001; 2003, Akcamete 2011; Lucus et al. 2013; Schein 2007; Turkaslan-Bulbul and Akin 2006; Liu et al. 2011). These efforts include academic research studies and data standardization from agencies and organizations, such as Building Smart Alliance and National Building Information Model Standard (NBIMS) development teams.

Existing aspect models and standards that consider the FM domain's needs are various and include several examples, such as Construction Operations Building Information Exchange (COBie), HVAC information exchange (HVACie), Automating Equipment Information eXchange (AEX), and Industry Foundation Classes (IFC). The objective of COBie is to define and capture information that is created in the design and construction phases of a project and are necessary during the facilities management phase so that a better handover of information from the construction phase to the operation phase of projects is enabled (East 2007). Though COBie focuses on information for FM, it basically contains as-designed and as-built information, but does not contain information that is generated during facility operation and maintenance phase, such as the sensor readings for HVAC controlled parameters, and maintenance history for HVAC components, which are among the important information requirements for HVAC mechanics for troubleshooting. As complimentary to COBie, HVAC information exchange

(HVACie) is under development to define exchange specifications for the capturing and delivery of life-cycle information about HVAC systems (Hitchcock et al. 2012). Currently, HVACie has been incorporated into the lasted version of IFC (i.e., IFC4) in HVAC domain and will be discussed in the next section together with IFC schema. In addition to these, Automating Equipment Information eXchange (AEX) project is developed to promote information exchange of major equipment in capital facilities, such as pumps, fans, motors and chillers (FIATECH 2009), which mainly focuses on the design data of facility equipment, and fails to provide flexibility in representing the information required in the operation and maintenance of facility equipment.

IFC is an open data schema for representing BIM and aims to improve information exchange and sharing among various participants in the whole life-cycle of Architecture Engineering Construction and Facilities Management (AEC/FM) projects (Building Smart Alliance 2011). Currently, the latest version of IFC schema is 2×4 (IFC4), which mostly represents the HVAC related information in its two domains, as the HVAC domain (i.e., from HVACie schema) and the Building Control domain. IFC covers a wide range of information that is valuable for troubleshooting of HVAC related problems, including but not limited to the location of HVAC components (IfcObjectPlacement, IfcRelContainedInSpatialStructure), HVAC zones (IfcSpatialZone), control relationships (IfcRelFlowControlElement) and connectivity relationships (e.g., IfcDistributionPort, IfcRelConnectsPortToElement) between HVAC components, the setpoints of controlled parameters (e.g. Pset_SensorTypeTemperatureSensor.SetPointTemperature), the readings of measured parameters (e.g., Pset_SensorHistory.Value), and the operation statuses of HVAC components (e.g., IfcDamper.Pset_DamperPHistory.DamperPosition). Beyond these data items, various other information items, such as the types of HVAC systems, the complaint logs in spaces, and the maintenance history of HVAC components are required for the troubleshooting of HVAC related problems but are not explicitly represented in the current IFC schema. Despite the limitations of IFC's representation for troubleshooting of HVAC related problems, this research builds on top of IFC and extends IFC because IFC has more coverage in terms of the required facility and HVAC system information than other related data standards.

In addition to the aforementioned data standards, various research studies looked into information representation for FM (e.g., Wix et al. 1999; Yu et al. 2000; Hassanain et al. 2001; 2003, Akcamete 2011 and Lucus et al. 2013). Though these research studies have commonalities in terms of information representation for FM, they differ in terms of their scopes and main areas of focus. These studies can be grouped based on their main area of focus into two categories as (a) research studies that looked at information representation for general maintenance tasks (e.g., Wix et al. 1999; Hassanain 2001, 2003; Akcamete 2011; Lucus et al. 2013) without differentiating them as corrective, preventive or predictive maintenance, and (b) research studies that looked at information representation for HVAC systems. The first group of research studies focused on supporting the planning of maintenance activities either in regular commercial buildings (e.g., Wix et al 1999, Hassanain et al 2001) or in large healthcare facilities which would require the linkage with healthcare activities (e.g., Lucus et al. 2013), but were not specifically related with HVAC systems. The second group of research studies focused on developing information models related with HVAC systems (e.g., Schein 2007; Turkaslan-Bulbul and Akin 2006; Liu et al. 2011) and are more related to the research presented here. Such studies focused on representing information regarding different aspects of HVAC systems, such as for supporting building commissioning process (e.g., Turkaslan-Bulbul and Akin 2006), providing information regarding building automation systems (e.g., Schein 2007), and functional representation of HVAC components (e.g., Liu et al. 2011). However, none of these studies have looked into information representation for troubleshooting of HVAC related problems and have gaps in terms of what they represent and what needs to be represented for supporting troubleshooting process for HVAC systems. The research presented in this paper builds on the domain information represented in data standards and related previous research studies however, extend these studies by developing reasoning mechanisms that utilize the information stored in information models to identify applicable causes of HVAC related problems and provide the right set of information to HVAC mechanics while troubleshooting.

In summary, due to the limitations of existing HVAC troubleshooting manuals/guidelines, FDD approaches, and BIM for FM related research studies in supporting the troubleshooting process, the research presented in this paper mainly augments the existing body of knowledge in the area of using BIM for facilities maintenance with a focus on HVAC related problems. The HVAC troubleshooting manuals/guidelines provided the right resources to understand the possible causes for HVAC related problems, and the related ASHRAE handbooks provided the foundation for representing the type enumerations for HVAC systems/components and the set of design constraints for a standard HVAC system configuration.

3.2 An automated approach to support troubleshooting of HVAC related problems

The approach presented here aims to bring a consistent and systematic way of checking components and facility/system information for better management of workforce distribution in CM of HVAC systems. The objective of this research study was to develop an automated approach to identify applicable factors/causes that could lead to the reported problem and retrieve required information for the listed causes in order to support troubleshooting of HVAC related problems. The HVAC systems focused in this study are centralized secondary HVAC systems, which are typically installed within buildings, and the primary HVAC systems such as chiller plants, which are usually located outside of buildings (ASHRAE 2008), are not within the scope of this research.

While conducting this research, I did a thorough domain knowledge analysis in relation to HVAC systems and troubleshooting process (as presented in Chapter 2), developed a data model and a set of reasoning mechanisms that reason with the underlying data model for the stated objective. Through extensive literature review, data standards investigation and parsing, and using the findings of the domain knowledge analysis, an integrated data model has been developed and used as the underlying data and relationships to store the required information. Algorithms (i.e., reasoning mechanisms) have been developed to (a) automatically generate work order context, which defines the conditions under which a work order was generated in a given facility [Figure 5(a)], (b) automatically identify a generic set of applicable causes based on the given work order's context [Figure 5(b)], and (c) automatically refine the identified generic list of causes to a specific list of causes for a given facility and retrieve relevant information based on the configuration of the HVAC system serving a reported space [Figure 5(c)]. While developing these reasoning mechanisms, I defined the HVAC design constraints, topological relationships and information that are critical for the algorithms and implemented them in a prototype system to conduct the validation studies, as detailed in the validation part of this research. In a nutshell, the developed approach uses a given work order and the BIM of a facility as inputs, and automatically identifies applicable causes for HVAC mechanics to consider. It also retrieves required information associated with these applicable causes, so that HVAC mechanics can diagnose the real cause among the applicable causes. The reasoning mechanisms will be explained in the following sections together with the developed representation schema, which is provided in Figure 6.

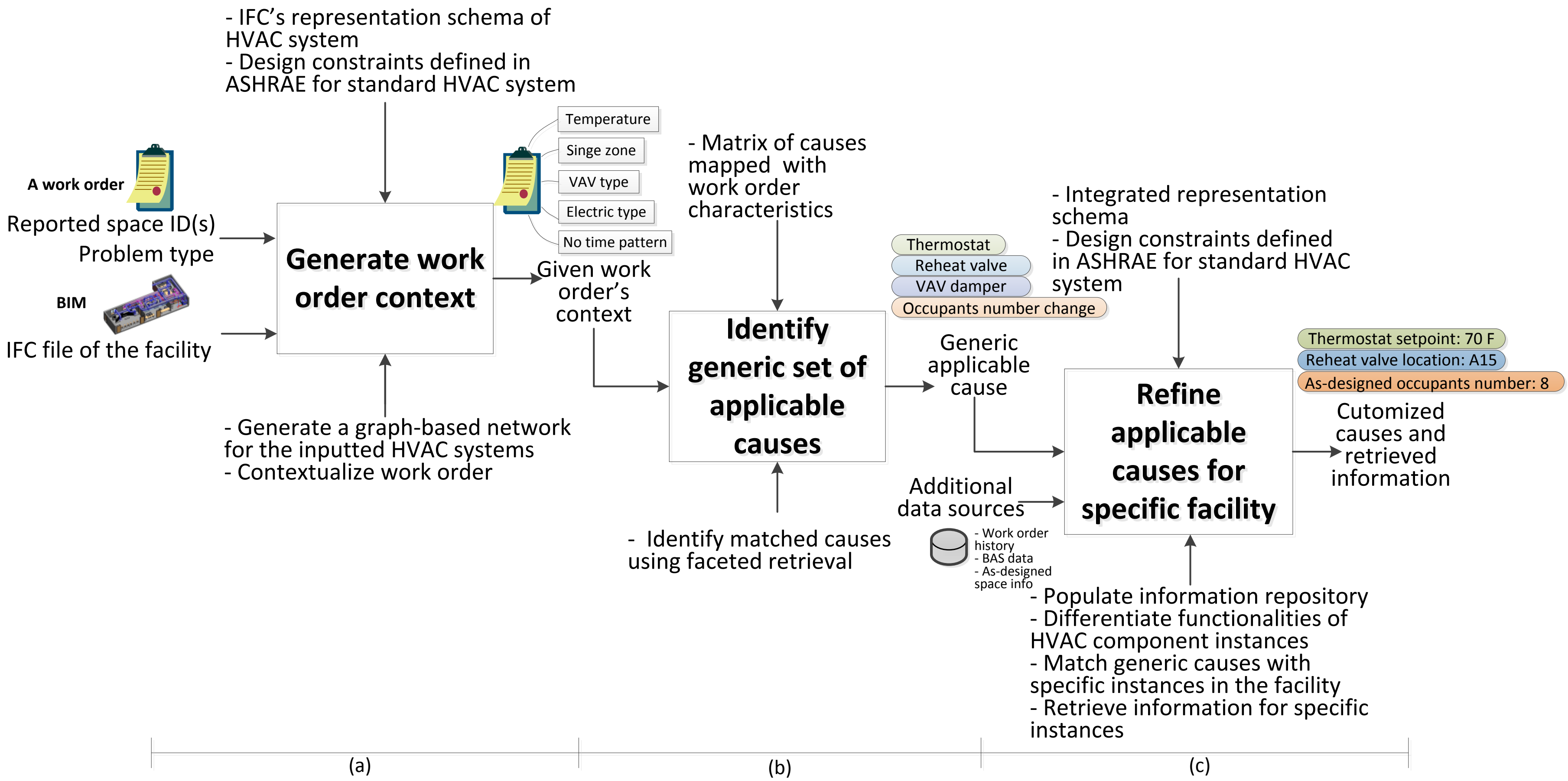


Figure 5. Process model for the developed approach in IDEF0 format

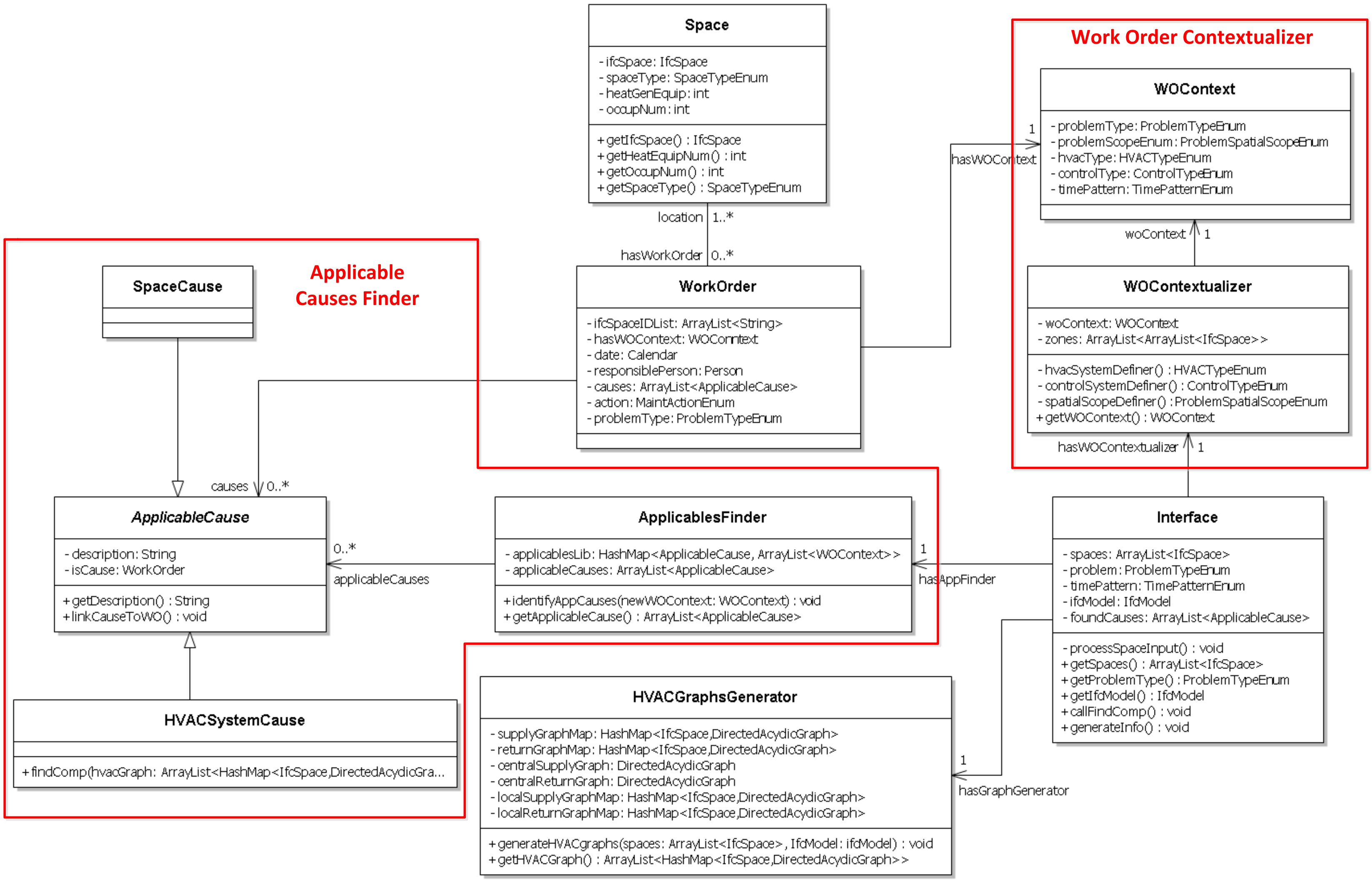


Figure 6. UML diagram of the representation schema for Work Order Contextualizer and Applicable Causes Finder

3.2.1 Concepts and terms related with HVAC systems and used in this study

The concepts and terms related with HVAC systems that I use to explain the reasoning mechanisms are provided below.

(1) Types of HVAC systems

According to HVAC system design standards (ASHRAE 2008; McDowall 2007; Pita 1998), centralized HVAC systems have three categories: 1) All-air systems, which only use air as the medium to condition spaces. All-air systems has various configurations and can be further classified as single-duct Variable Air Volume (VAV) systems (referred as VAV type), single-duct Constant Air Volume (CAV) systems (referred as CAV type), and dual-duct systems; 2) All-water systems only use water as the medium to condition spaces, and the most common ones are the systems that use radiators and fan coil units (FCU); 3) Air-water systems, which use both air and water to condition spaces and combine the components in all-air and all-water systems.

(2) Central systems and terminal systems

For all-air and air-water types of HVAC systems, the centralized air handling units (i.e., central systems) are responsible for the primary cooling, heating, ventilation and (de)humidifying of the air being supplied to conditioned spaces. Between the primary air distribution system and the conditioned spaces are the terminal units/systems, which further control the temperature and volume of air being supplied to each individual space to maintain different desired conditions (ASHRAE 2008), as shown in Figure 7. For all-water systems, there are no centralized air handling units, and terminal systems (e.g., radiators, FCUs) are responsible for the cooling and heating for each space (ASHRAE 2008).

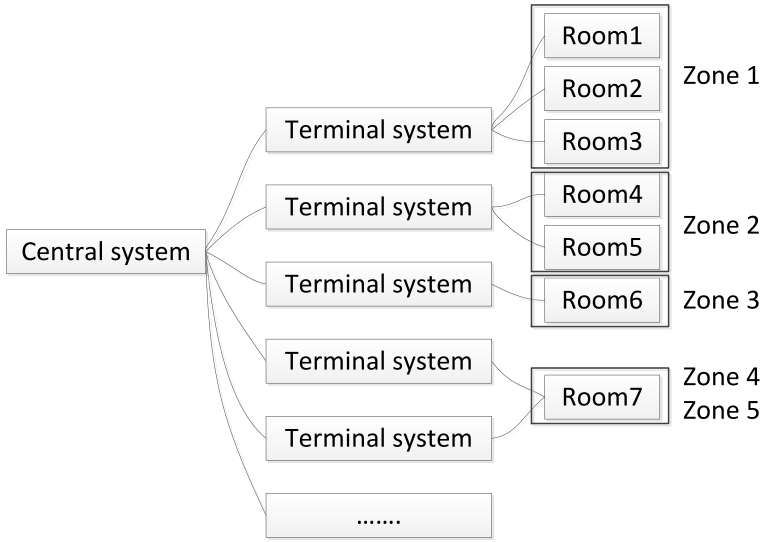


Figure 7. Relations between HVAC system central systems, terminal systems and zones

(3) Zones and rooms

An HVAC zone refers to a room/space or a group of rooms/spaces where the conditioning is controlled by the same thermostat, whereas a room is a partition of space per architectural requirements which does not necessarily need a separate control (ASHRE 2008; Pita 1998) Terminal systems are directly controlled by thermostats in each zones and thus one zone has one terminal system. As shown in Figure 7, the relationship between zones and rooms are various based on different requirements of the HVAC control: a zone can be composed of one room or multiple rooms, and multiple zones can constitute one room.

3.2.2 Module 1: Generation of a work order context

A work order context is represented as a class WOContext with 5 attributes (Figure 6), corresponding to the five characteristics of a work order: type of reported problems, the spatial scope of reported problems, the type of HVAC systems, the type of control systems, and the time pattern of reported problems (Figure 8). The definition of the five characteristics and their enumeration values were identified through a detailed research that included shadowing, interviews and focus groups with expert HVAC mechanics and detailed in Chapter 2.

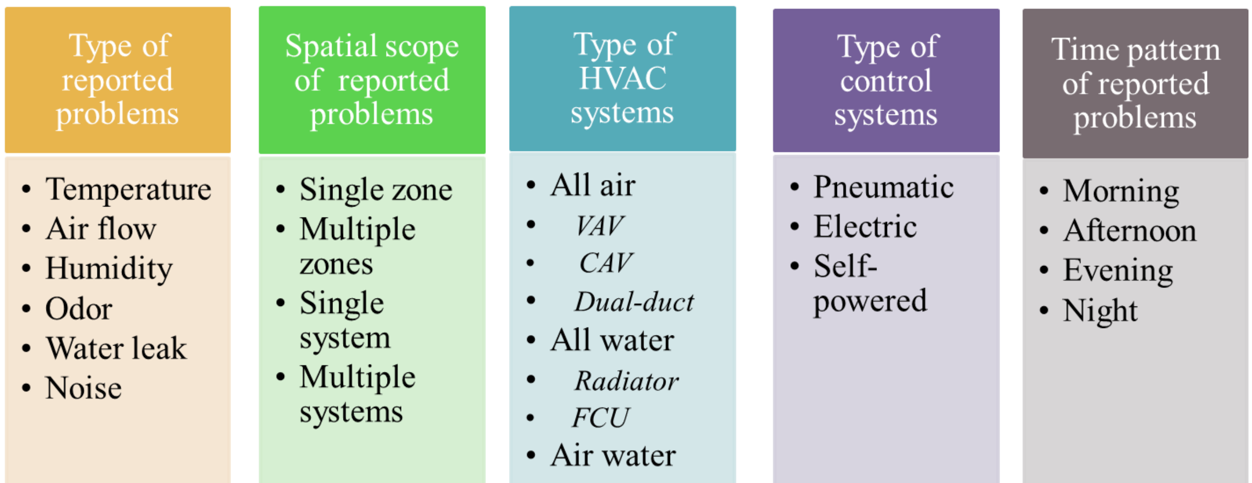
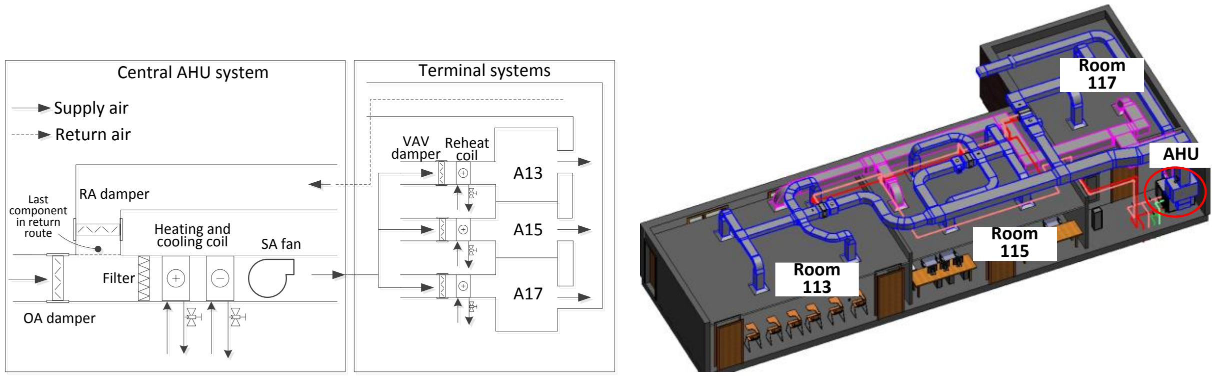


Figure 8. Characteristics of HVAC related work orders and enumerated values

The algorithm to generate the values for these five characteristics for a given work order is called the *Work Order Contextualizer* and the corresponding class that contains the algorithm is defined as WOContextualizer (Figure 6). The algorithm requires inputs from the work order about the affected space ID(s) and the reported problem type, and the IFC file which contains the information about the given facility. As shown in Figure 6, the *Interface* class accepts inputs of the problem type and space ID(s) as reported in a given work order, and an IFC file of the facility. The *problem type* is given in the descriptions from the reported work order. Users need to read the work order description and select a problem type and a time pattern option from the prototype interface based on the problem description reported by occupants. Based on the space ID(s) reported, all the corresponding *IfcSpace* instances are found from the IFC file. With these inputs, the *Work Order Contextualizer* identifies and labels the five characteristics of the given work order. The values for the type and time pattern of the reported problem are defined by the users directly, and the values for the type of HVAC system, the spatial scope of reported problem, and the type of control system need to be generated by reasoning with the IFC file, which are obtained through three sub modules, defined as the *HVAC System Definer,* the *Spatial Scope Definer,* and the *Control System Definer*, respectively, which will be explained in the following sections. Since this research builds on the IFC schema as the basis of the information repository, the general principle that I followed to develop the algorithms was to make the most use of IFC and eliminate arbitrary extension of the data schema. The rationale was: (a) if the needed information is already represented in IFC, directly read it from an input IFC file, (b) if the needed information has not been included in the current IFC schema but can be deduced by reasoning with existing representation, develop algorithms to deduce the value of the information, and (c) if the needed information has not been included in the current IFC schema, or can be deduced from existing representation, extend IFC's representation.

Knowing the components belonging to central systems or terminal systems is fundamental to define the type of the HVAC system and the spatial scope of a reported problem. Current IFC schema defines *IfcSystem* to represent group of components in the same system, but does not differentiate central systems or terminal systems. In order to differentiate components in central systems versus in terminal systems, I converted IFC's representation of HVAC systems to a graph-based representation due to its flexibility in extracting and simplifying topological information about facilities (e.g., Leite and Akinci 2012; Langenhan et al. 2013) and HVAC system components (Golabchi et al. 2013). Graphs are composed of a set of nodes and edges, and for HVAC systems each HVAC component could be represented as a *node* in the graph, and the flow direction is represented as the direction of an *edge* connecting two nodes. A class called *HVACGraphGenerator* is defined, which contains the algorithm to convert IFC's representation of HVAC systems to a graph-based representation. Connectivity of system components is represented in IFC via *IfcDistributionPort* (i.e., an entity representing the inlet/outlet of a component through which air/water flows), *IfcRelConnectsPortToElement* (i.e., an entity representing the connection between a distribution port and a component) and *IfcRelConnectsPort* (i.e., an entity representing the connection between two distribution ports). *IfcDistributionPort* has an attribute of *IfcFlowDirectionEnum* (e.g., SOURCE, SINK) to indicate the air and/or water flow direction. Using the connectivity between HVAC components and the flow direction, *HVAC Graph Generator* first traces all connected components in the supply air ductwork route related to a given space from the supply air diffusers to outside air intake and generates the graph-based network. Figure 9 shows a standard HVAC system of VAV type that conforms to the ASHRAE design constraints, with its schematic diagram [Figure 9(a)] and the rooms it serves [Figure 9(b)] as an example. The graphs representing HVAC components on the supply route serving room 117 and 115 are shown in Figure 10. The results are then stored in a map called *supplyGraphMap* as an attribute in *HVACGraphsGenerator* class (Figure 6). Each element in the map is a pair of a key and a value. The *supplyGraphMap* has the *IfcSpace* instance, representing the space reported in a given work order, as the key, and all HVAC components serving the space are stored in a Directed Acyclic Graph as the value. Similarly, the components in the return/exhaust air routes are traced from the return/exhaust air diffusers to the exhaust air outtake or the last component in return route [Figure 9(a)] and stored as *returnGraphMap*. The process will be repeated for each of the remaining spaces in the same system(s) as that of the reported space, so that all components in the system(s) are labeled.



(a) Schematic diagram of the system and rooms (b) Physical layout of the system and rooms

Figure 9. An example HVAC system and the rooms it serves

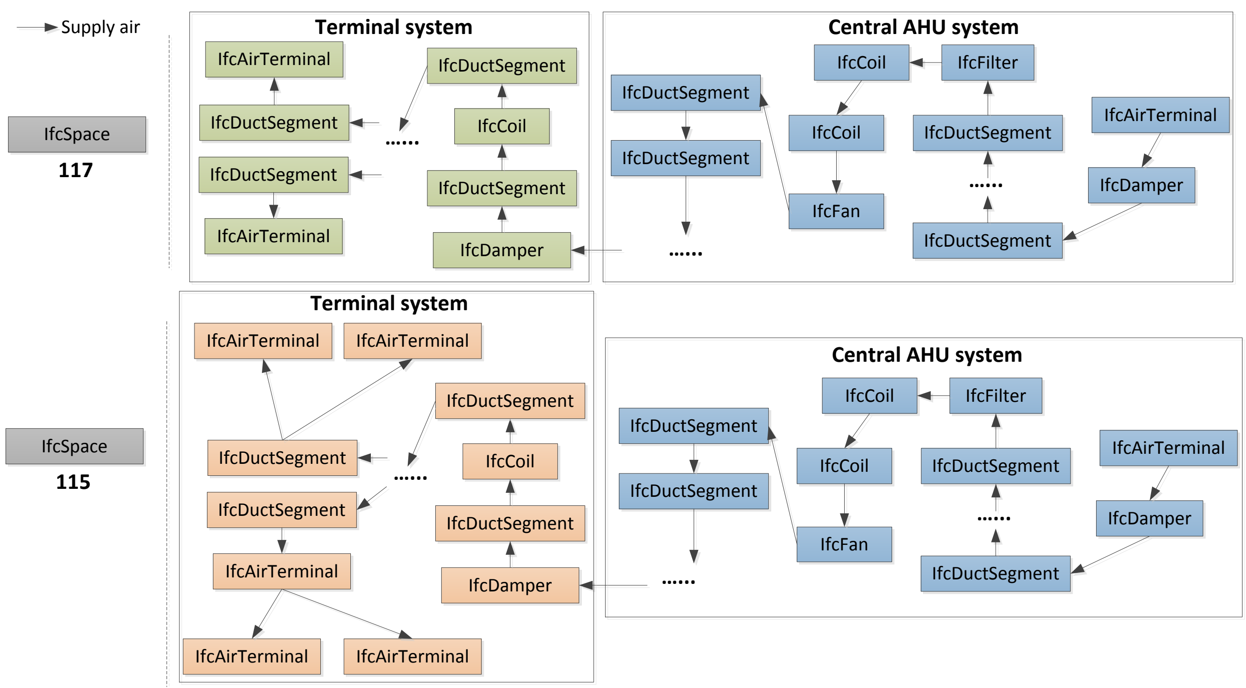


Figure 10. Graph-based network representation of the HVAC system and the differentiation of central system versus terminal systems

When the *supplyGraphMap* and *returnGraphMap* are generated, the next step is to differentiate the components that belong to central and terminal systems. This process is done through comparing the graphs for all spaces stored in a *supplyGraphMap*. The basic logic is that components that belong to a central system should appear in all the graphs regardless of the spaces that are conditioned in a given system, and the remaining components should belong to terminal systems. As shown in Figure 10, the components that were found in all graphs will be labeled as components of the central system, whereas the rest of the components will be labeled as components of terminal systems for individual graphs.

As mentioned before, three sub-modules *HVAC System Definer, Spatial Scope Definer, and Control System Definer* were developed to generate a work order context:

(1) HVAC System Definer: The type of HVAC system is not explicitly represented in IFC, but can be deduced by checking the type of terminal components or terminal systems serving the spaces represented in the IFC file. The *HVAC System Definer* requires certain set of information and design constraints defined in ASHRAE handbook (2008) to automatically differentiate the HVAC system type represented in an IFC file. There are general expectations about the set of components that typically appear in a given HVAC system. For all-air systems, since only air is used as the medium, and the conditioned air is distributed through ductwork to the served spaces, the only terminal components contained in spaces will be air diffusers or grilles. Hence, if only air diffusers are found in the reported space represented in the input IFC file, the system will be labeled as all-air system. Air-water systems use both air and water to condition spaces, and thus this type of systems will not only need air diffusers to distribute conditioned air to the spaces, but also will need terminal units that can use water as the conditioning medium, such as Fan Coil Units (FCU) and radiators. Hence, if both air diffusers and water-side terminal units are found in

the reported space in the inputted IFC, the system will be labeled as an all-water system. All-water systems only use water as the medium to condition spaces, and thus no air diffusers will be observed in spaces served by such systems. Hence, if only water-side terminal units are found in the reported spaces in the inputted IFC file, the system will be labeled as an all-water system. This process is shown in Figure 11.

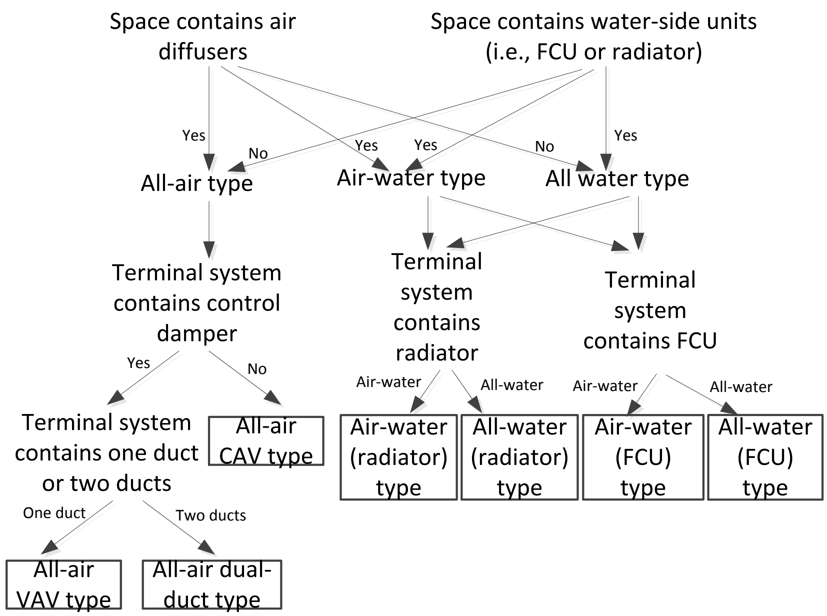


Figure 11. Reasoning process for *HVAC System Definer*

Furthermore, to differentiate the subtypes for the systems, the components contained in terminal systems need to be analyzed. Air-water and all-water systems can be further categorized by checking if their terminal systems contain FCU or radiator. For all-air systems, according to ASHRAE handbook (2008), CAV systems do not have control dampers at terminal systems since the air volume is not modulated; both VAV and dual-duct systems have control dampers at corresponding terminal systems, but there is only one duct connected with the intake side of a VAV damper, while two ducts are connected with the intake side of a dual-duct mixing box.

These design constraints were used in the reasoning to differentiate the subtypes of the systems, as shown in Figure 11. These constraints were implemented in the *HVACSystemDefiner* method in the *WOContextualizer* class to differentiate system types (Figure 6).

(2) Spatial Scope Definer: The spatial scope of a problem can be determined by checking the number of HVAC zones or systems serving the reported space(s). A variable of *zones* (i.e., a room/space or a group of rooms/spaces) is defined in the WOContextGenerator class. The variable *zones* can be obtained by parsing an IFC file to read the *IfcSpatialZone* entities. Because the IFC file exported from the BIM tool used in this study do not contain *IfcSpatialZone* entities I deduced the value of *zones* by reasoning with the *supplyGraphMap* variable to check the mapping relationships between the rooms and terminal systems. First of all, if *zones* is an empty variable, it means the system is a single-zone system (the problem spatial scope will be labeled as a *single zone/system*) because no terminal systems exist, otherwise the system is a multi-zone system. If the system is a multi-zone system, the reported space(s) will be looped through and checked if they contain different zones (the problem spatial scope will be labeled as *multiple zones*), or they are in the same zone (the problem spatial scope will be labeled as a *single zone*). In addition, if the reported space(s) are not contained in the same system, the spatial scope will be labeled as *multiple systems*. Figure 12 shows the reasoning process for *Spatial Scope Definer*. This process is implemented in spatialScopeDefiner method in the *WOContextualizer* class (Figure 6).

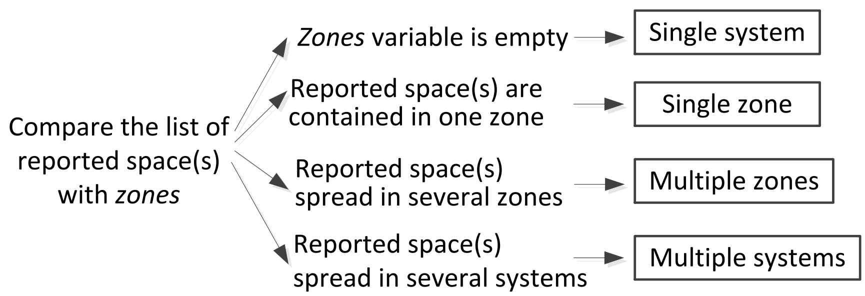


Figure 12. Reasoning process for *Spatial Scope Definer*

(3) Control system definer: The type of control systems is easier to obtain by parsing the IFC file because IFC 2x4 defines different types of control mechanisms for actuators in the *IfcActuatorTypeEnum* entity, such as an electrical actuator and a pneumatic actuator. Hence, the type of actuators contained in HVAC systems serving the reported spaces can be used to determine the type of control system used by HVAC systems.

Finally, the values identified through these reasoning mechanisms for the 'type of reported problems', the 'spatial scope' of reported problems, the 'type of HVAC systems', the 'type of control systems', and the 'time pattern' of reported problems constitute an instance of the *WOContext* class. This attribute appears in the *WOContextGenerator* class. The generated work order context will be used in the next step to identify the generic set of applicable causes for reported problems.

3.2.3 Module 2: Identification of applicable causes for reported HVAC problems

This step aims to automatically identify the generic set of applicable causes for a given work order context. The algorithm in this step has been referred to as Applicable Cause Finder, and is implemented in the ApplicablesFinder class (Figure 6). The work order context has impacts on the applicable causes, and the fundamental requirement is to map possible causes to the possible work order characteristics. The causes include common HVAC components, and also include space related causes, such as space usage type changes.

A matrix was defined and used in this research for each of the work order characteristic and their mapping to applicable HVAC components/space related causes. The mapping between causes and problem types is the synthesized work from review of HVAC troubleshooting manuals/guidelines, and case studies including shadowing of 40 work orders, interviews, and focus groups conducted with 28 HVAC mechanics from three different FM organizations. During shadowing work, the causes that HVAC mechanics considered or checked for different work orders were recorded, and during interviews and focus groups, HVAC mechanics were asked to list possible causes they would consider and check for different types of problems. The mappings between possible causes and spatial scope of the reported problems, type of HVAC systems and type of control systems have been defined through parsing related ASHRAE handbooks, HVAC design manuals and guidelines (ASHRAE 2008; McDowall 2006; Kreider et al. 2001; Pita 1998).

There are 40 possible causes in the cause library, and the size each matrix is 40xn, where n represents the number of enumerations for each work order characteristics listed in Figure 8. Figure 13 shows example mappings from the matrices. Different types of problems will have different applicable causes. For example, a thermostat will be an applicable cause only for temperature or air flow problems. Hence, when an odor problem is reported, thermostats will not be among the applicable causes and information about thermostats will not be retrieved.

Example of causes	Type of reported problems	Spatial scope of reported problems	Type of HVAC systems	Type of Control systems
Thermostat	Temperature; Air flow	Sing zone	All HVAC system types	Pneumatic; Electric
Reheat valve	Temperature; Water leak; Noise	Sing zone	CAV; VAV; Air-water (Radiator)	Pneumatic; Electric
Supply fan	Temperature; Air flow; Odor; Noise	Multiple zones; Single system	All-air Air-water	Pneumatic; Electric
Central Cooling coil	Temperature; Air flow; Humidity; Odor; Water leak	Multiple zones; Single system	All-air Air-water	Pneumatic; Electric
Air compressor	Temperature; Air flow; Odor; Noise	Multiple zones; Single system; Multiple systems	All HVAC system types	Pneumatic
Space type change	Temperature; Air flow; Humidity; Odor;	All spatial scopes	N/A	N/A

Figure 13. Examples of mappings from the matrices of possible causes of problems and work order characteristics

HVAC mechanics use *spatial scope of reported problems* to determine whether there is a need to check components in the terminal systems or central systems. For example, in a multi-zone system, if a temperature problem only happens in one of the zones, components in terminal system will be identified among the applicable causes, such as thermostat and reheat valve as shown in Figure 13. On the contrary, in the same multi-zone system, if a temperature problem happens in various zones, components in the central system are among the applicable causes, such as supply fan and central cooling coil as shown in Figure 13. Therefore, for *a multi-zone system*, the components that appear in terminal systems are mapped with problem spatial scope of *single zone*, and the components appear in central systems are mapped with the problem spatial scope of *multiple zones*. In addition, there are no terminal systems for a single-zone system, and thus components in central system are mapped with the problem spatial scope of *single zone/system*.

Based on the HVAC system design standards, there are certain expectations about the types of components that could be part of a given *type of an HVAC system*. For example, reheat valve should not appear in dual-duct type of systems because the supply air temperature is controlled by adjusting the air volume from hot and cold decks, instead of through reheat coil and reheat valve. Similarly, supply fan and central cooling coil are components that can appear in all-air and air-water type of HVAC system, but not in all-water type of HVAC system, as shown in Figure 13. Furthermore, the *type of control systems* will affect the applicable auxiliary control devices. For example, air compressors can only appear in pneumatic type of control systems. At last, *time pattern of reported problems* can be used to find match between the reported problem and the schedule of HVAC equipment. For example, if a noise problem is reported to be always happening in the afternoon a nearby AHU is scheduled to be only running in the afternoon, the AHU supply/return fan is very likely to be the source of the problem. But *time pattern of reported problems* is not associated with specific components and thus not included in the matrix.

In term of implementation of the algorithm of Applicable Causes Finder, AND logic is used among the characteristics of work orders to identify the applicable causes. For example, reheat valve is among the applicable causes for a work order that has the context of (***temperature problem***) AND (***single zone***) AND (***CAV system***) AND (***Pneumatic control***). Change in the characteristics that constitutes a work order context would result in the change of applicable causes. For example, reheat valve will not be among the applicable causes for a work order with (***air flow problem***) AND (*single zone*) AND (*CAV system*) AND (*Pneumatic control*), or work order with (*temperature problem*) AND (***multiple zones***) AND (*CAV system*) AND (*Pneumatic control*), or work order with (*temperature problem*) AND (*single zone in a multi-zone system*) AND (***dual-duct system***) AND (*Pneumatic control*).

The matrix with mapping between the possible causes and work order characteristics are stored in *applicableLibrary* in the *ApplicablesFinder* class, as shown in Figure 6. A class *ApplicableCause* is defined as the super class of all causes, and it has two subclasses – *HVACComponentCause* and *SpaceCause*. *HVACComponentCause* is the super class of all HVAC component related causes, such as *ThermostatCause*, *ReheatCoilCause*, etc., and *SpaceCause* is the super class of all space related causes, such as *SpaceTypeCause* (i.e., indicating the space usage type changes), and *OccupancyNumCause* (i.e., indicating the change in number of occupants in reported spaces). The causes and their associated list of work order contexts are stored as key/value pairs in the variable called *applicableLibrary*. Given a generated work order context from the first module, *Applicable Causes Finder* will loop through the *applicableLibrary* list to identify all applicable causes. For a specific cause, if a match is found between the given work order context and one of predefined work order contexts associated with the cause, the cause will be identified as applicable and added to *applicableCauses,* which is defined to store the identified set of applicable causes. In the next module, the identified list of applicable causes will be used to find corresponding HVAC components and spaces represented in an IFC file to refine the causes based on the specific configuration of the facility and the system at hand.

What worth mentioning here is that this step can eliminate the causes that cannot possibly be applicable for a given work order context, but the identified causes are generic and not all of the identified HVAC components may appear in a specific HVAC system. This is due to HVAC system's customized configurations. Each HVAC system is configured differently and variations are common (Kreider, J. F. et al. 2001). Having an HVAC component in a certain type of HVAC system does not necessarily mean that all instances of that type of system will have that component. For instance, a VAV fan can be part of a terminal system in a VAV type of HVAC system, but not all VAV systems are configured to have terminal fans. Hence, it is necessary to refine the causes that are identified based on the configuration of a specific HVAC system. This reasoning is detailed in the next section.

3.2.4 Module 3: Refinement of applicable causes for specific facility and retrieval of required information

To retrieve the required information associated with the identified applicable causes, the corresponding instances in the specific facility (i.e., in the IFC file) should be found. There is a challenge here in finding the corresponding HVAC components represented in IFC because current IFC standard does not differentiate HVAC components of the same type with different functions (Yang and Ergan 2014a). For example, there are multiple dampers with different functionalities existing in HVAC systems, such as outside air (OA) damper, return air (RA) damper, exhaust air (EA) damper, mixed air (MA) damper, and zone dampers, but all of these dampers are represented using the *IfcDamper* class. When the problem type changes, the corresponding applicable damper types also change. When a damper with specific function is among the applicable causes and its information needs to be retrieved, it is not possible to directly identify the instance and retrieve its information because all dampers are represented as *IfcDamper* in the IFC schema. It has been identified that several HVAC components that have the same type can perform different functions, and these include dampers, coils, valves and fans (Yang and Ergan 2014a). Similar to dampers, different instances of coils, valves, and fans are represented as *IfcCoil*, *IfcValve*, and *IfcFan* respectively in the IFC schema with no functional differentiation.

In order to address this challenge of distinguishing the HVAC component instances that are represented with the same IFC class but have different functional roles in an HVAC system, I used the HVAC design constraints as documented in HVAC handbooks (Yang and Ergan 2014a; ASHRAE 2008; McDowall 2006; Kreider et al. 2001; Pita 1998). These constraints are defined in ASHRAE based on the topological hierarchies (appearing in a central system vs. a terminal system), the topological relationships (i.e., where the components appear relative to the surrounding components) and the air flow direction (i.e., in supply air flow direction vs. in return/exhaust air flow direction). Table 9 shows the design constraints for different damper subtypes. For example, *outside air damper* is always the first damper connecting to outside intake, and it always appears in a central system at the supply air flow direction. Using the graph-based representation of HVAC systems generated from the first module, these constraints can be extracted. All of the HVAC components in central system are already stored in a directed acyclic graph *centralSupplyGraph*, and the first element in the graph is an outside air intake. Tracing from the outside air intake following the graph edges' direction, the first control damper that is encountered in the graph will be identified as the outside air damper. Similarly, to identify a *zone damper* for a space, *localSupplyGraphMap* will firstly be used to get the graph that represents the terminal system for that space. For a space i, represented as SP_i, the corresponding graph is the local supply graph, represented as LSG_i. The last element in LSG_i should be a supply air diffuser, and tracing from the supply air diffuser, the first control damper that is encountered in the graph will be identified as the zone damper. Each subtype of the damper follows a unique set of constraints and can be used to differentiate from other dampers. The complete list of damper constraints has been summarized in Table 9.

Table 9. Constraints to distinguish dampers with different functions (Yang and Ergan 2014a)

Damper subtypes	**Topological hierarchy**	**Topological relationships with spaces or other components**	**Air flow direction**
Outside air damper	Central system	Directly connects to outside intake	Supply air direction
Return air damper	Central system	Directly connects to served space	Return/exhaust air direction
Exhaust/relief air damper	Central system	Directly connects to outside without going through damper	Return/exhaust air direction
Mixed air damper	Central system	Not needed	Return/exhaust air direction

Coils can be of types central heating coils, central cooling coils, central reheat coils and terminal reheat coils. All of the coils should appear in the supply air flow direction based on the fundamentals of HVAC design. Heating/reheat coil can be differentiated from cooling coil by the hydronic system they belong to- i.e., hot water/steam or chilled water systems. Table 10 shows the ASHRAE design constraints for all coil subtypes. These constraints are used in the reasoning to differentiate the coils with different functions, and the corresponding valves controlling the flow of hot/chilled water for these coils can be traced via the pipework connected with coils.

Table 10. Constraints to distinguish coils with different functions

Coil subtypes	**Topological hierarchy**	**Topological relationships with other components**	**System type**
Central heating coils	Central system	Appear before cooling coil	Hot water or steam
Central cooling coils	Central system	Not needed	Chilled water
Central reheat coils	Central system	Appear after cooling coil	Hot water or steam
(Terminal) reheat coils	Terminal system	Not needed	Hot water or steam

Regarding the fan subtypes, there are supply fans, return fans, exhaust fans, and VAV fans. Supply fans and VAV fans should appear in supply air flow direction, while the former belongs to a central system, the latter belongs to a terminal system. Return and exhaust fans appear in ductwork coming out of the served spaces, i.e., at the return air exhaust air flow direction. The difference is that exhaust fans directly draw air to the outside, while return fans recirculate air back to supply air systems. Table 11 shows the constraints for different fan subtypes.

Table 11. Constraints to distinguish fans with different functions

Coil subtypes	**Topological hierarchy**	**Topological relationships with other components**	**Air flow direction**
Supply fans	Central system	Not needed	Supply air direction
Return fans	Central system	Connected to supply air duct at the air flow direction	Return/exhaust air direction
Exhaust/relief fans	Central system	Connected to outside at the air flow direction	Return/exhaust air direction
VAV fans	Terminal system	Not needed	Supply air direction

Each of the HVAC components that need to be differentiated has unique set of constraints that can be obtained from IFC to deduce the specific function of that component. As shown in Figure 6, each of the subclasses of *HVACSystemCause* overrides the method of *findComp*, which individually implements the constraints of the specific component to identify the instance represented in IFC. For example, the *findComp* of *ReheatCoilCause* will search for the specific *IfcCoil* that can satisfy all the constraints defined for reheat coils. For each of the applicable HVAC component listed as applicable causes using the second module, the method will run to identify the corresponding IFC instances. This process also further customizes applicable HVAC component related causes for the given work order. The last module only uses HVAC system type to eliminate inapplicable components for the specific type of HVAC system, and it is still possible that the specific system does not contain all of the components. If the *findComp* method cannot find a HVAC component in the facility specific IFC model that meets all the constraints, the HVAC component related cause will be eliminated from the set of applicable causes.

The information that needs to be retrieved per component is documented in details in Chapter 2. I extended IFC's representation by adding the required information that was not covered in IFC. As shown in Figure 6, *HVACComp* class is associated with *WorkOrder* class, which indicates all the historical work orders that are related with the HVAC component. The work order class contains the required historical information, including maintenance date, actions, responsible personnel, etc. Similarly, for space related causes, space related information needs to be retrieved. IFC does not have information about number of heat-generating equipment in spaces, and this information is added to the *Space* class.

The representation schema as shown in Figure 6 also serves as the underlying data structures to integrate information from data sources. The HVAC component dynamic information comes from Building Automation Systems (BAS); the historical work order information is stored Computerized Maintenance Management System (CMMS); and space related information is represented in BIM. Data from these different sources was exported or prepared in .csv file and used as inputs together with IFC file to populate an integrated information repository, from which the required information about the HVAC components and spaces will be retrieved for HVAC mechanics.

3.3 Implementation and validation

A prototype was developed using Java to implement the approach and understand the generality of the approach in pinpointing the applicable set of causes for a given facility. The prototype uses open source Java Toolbox for IFC 4 developed by IFC Tools Project (http://www.ifctoolsproject.com) to read an IFC file. The prototype accepts inputs of .csv files containing data from other sources. As shown in Figure 14(a), facility-specific IFC file and data from other sources can be loaded. Users also need to input work order information, which include selecting a problem type [Figure 14(b)], and typing in the space ID(s) where the problem occurs [Figure 14(c)]. After users define these inputs, the system automatically generates the context for the given work order, finds applicable causes for the reported problem in the specified space(s) and retrieves relevant information. The work order context is displayed to users at the top of the interface [Figure 15(a)]. Applicable causes are listed on the left [Figure 15(b)], and when users select different causes, their relevant required information will be displayed on the right [Figure 15(c)]

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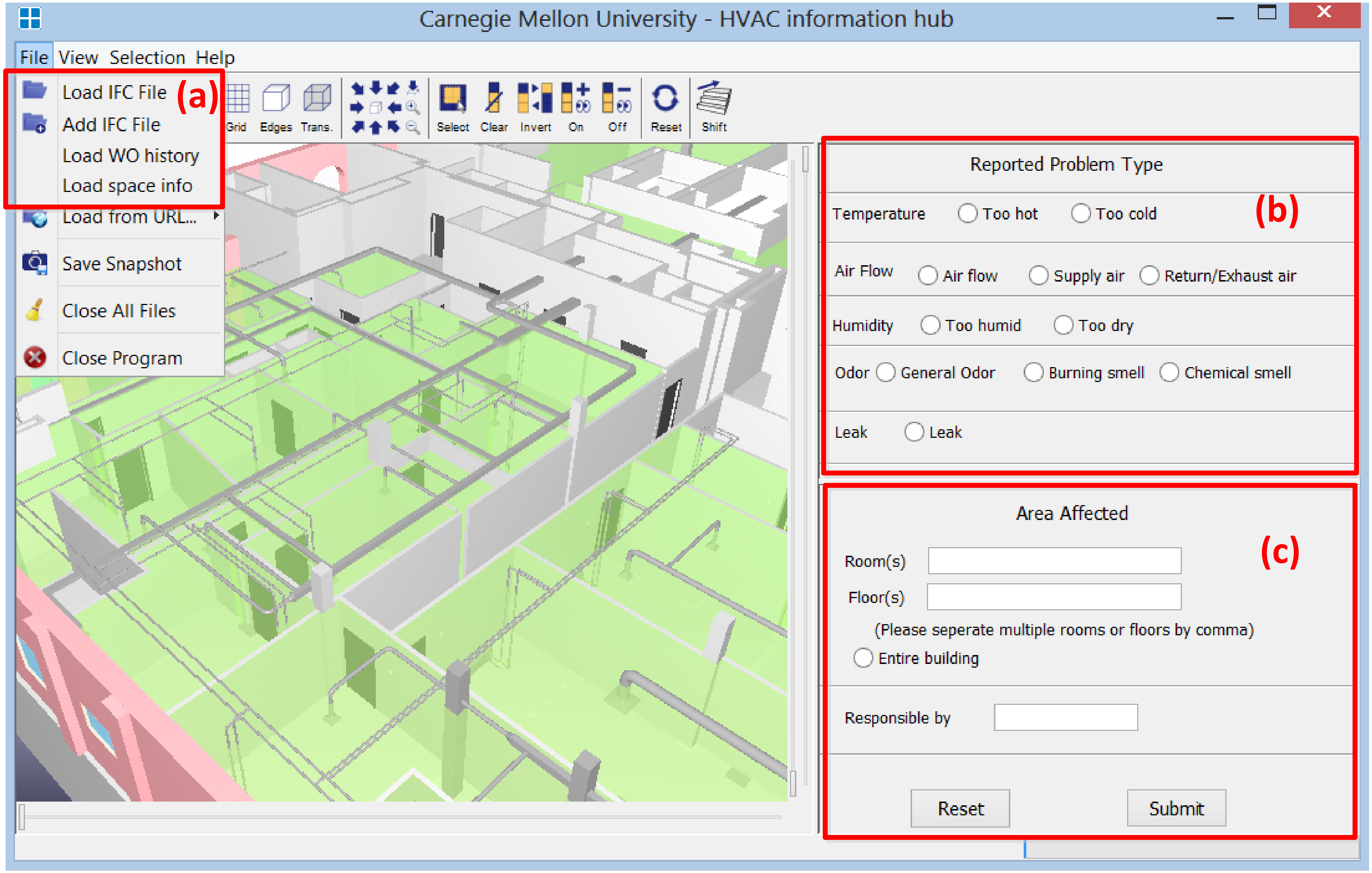


Figure 14. Prototype input interface

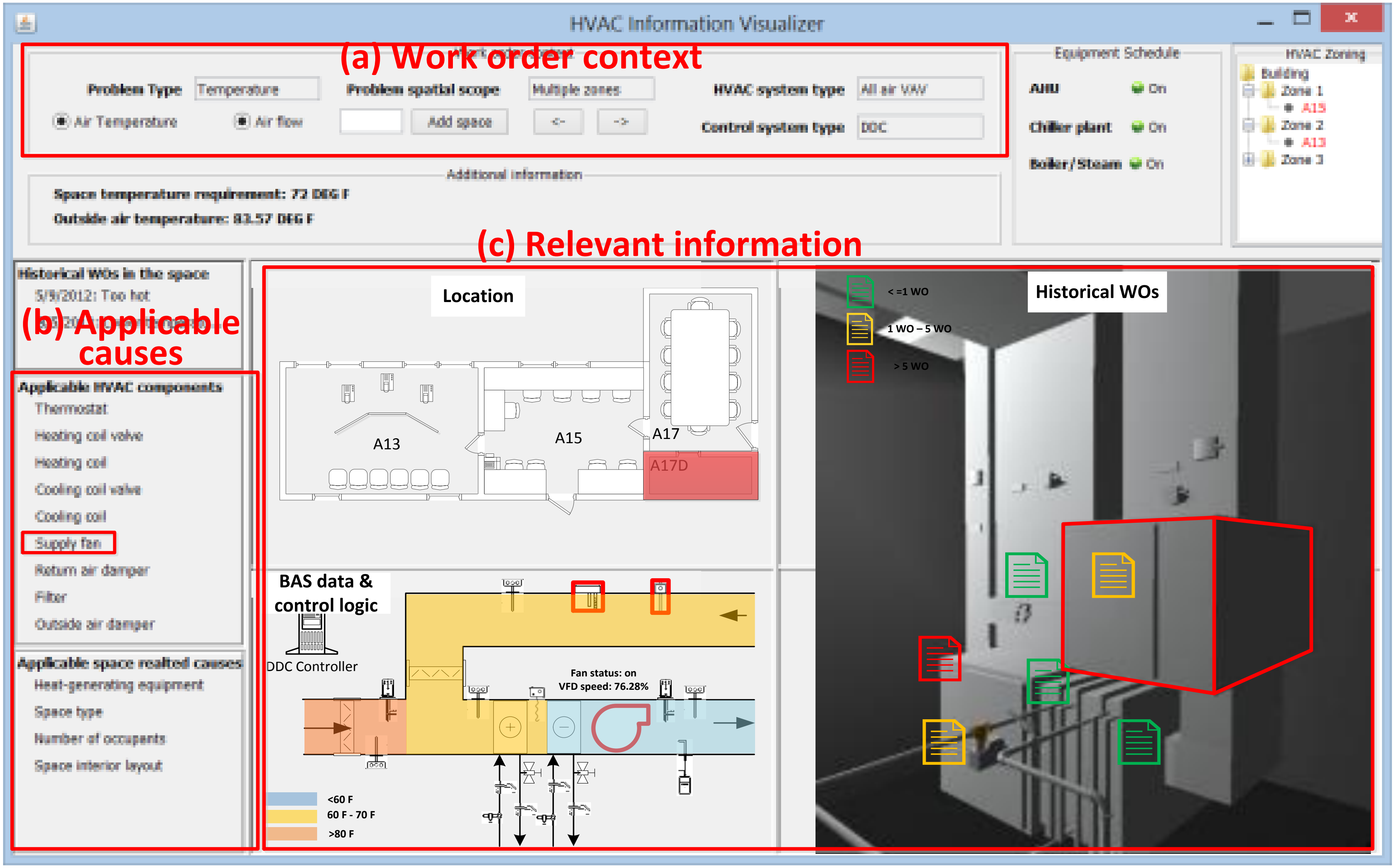


Figure 15. Prototype output interface

The approach has been validated for its *efficiency* and *accuracy* of identifying applicable causes for different work order contexts, for its *efficiency* in reducing the search space of applicable causes for any given work order, and its *accuracy* in terms of precision and recall to identify the right set of components for different work order contexts generated for all types of HVAC systems:

Efficiency = 100% × [1 - (number of applicable components) / (number of all components serving reported spaces)]

Precision = 100% × (number of retrieved and applicable components) / (number of retrieved components)

Recall = 100% × (number of retrieved and applicable components) / (number of all applicable components)

I conducted tests by changing the inputs to create different combinations of work order characteristics. Seven testbeds were modeled and used during the tests. All testbeds were selected from real buildings, where I had access to the design drawings and specifications. Each building had a different HVAC system. The seven testbeds were representative of all types of HVAC systems and the testbeds included an 1) all-air single-duct CAV system; 2) all-air single-duct VAV system, an, 3) an all-air dual-duct system, 4) an air-water (FCU) system, 5) an air-water (radiator) system, 6) an all-water (radiator), and 7) an all-water (FCU) respectively. Each model included a set of spaces and the complete set of HVAC components and ductwork used to condition those spaces, as shown in Figure 16. Also, all of these seven testbeds are multi-zone systems, and single-zone systems are not tested because they are simpler versions of multi-zone HVAC systems. Spaces in testbed 1 include a classroom, a cluster and a physics lab, testbed 2 has spaces of two clusters and a conference room, testbed 3 has a big ballroom, testbeds 4-7 are composed of office spaces. Furthermore, these testbeds also include three special scenarios in terms of the space and HVAC configurations: 1) in the testbed 1, the cluster is connected with the physics lab through an open space, which could cause the odor in lab space travelling to the cluster through the building pathway; 2) in the testbed 4, there are rooms in the same centralized supply air system, but not connected to the corresponding centralized exhaust system; 3) in the testbed 5, the ceiling plenum is used as the return air circulation space instead of return ductwork. These testebeds are expected to cause the drop in recall rate and they are selected to test how much they will affect the recall.

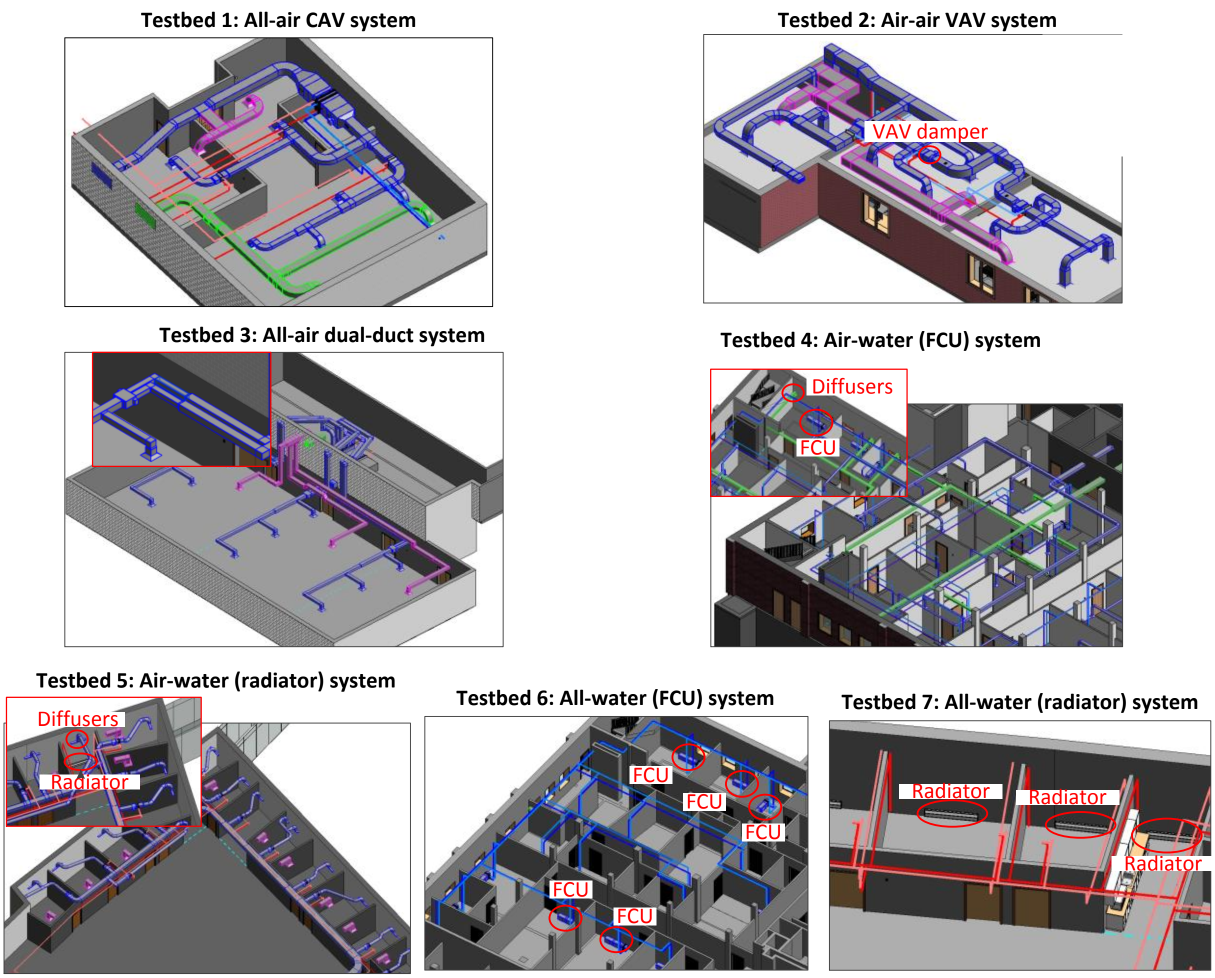


Figure 16. Snapshots of BIMs of the 7 testbeds

Using these seven testbeds, I changed the problem types (i.e., 6 different types) [Figure 14(b)], and used different space ID(s) [Figure 14 (c)] to create spatial scope of *single zone*, *multiple zones* and *single system* (scope of multiple systems is not tested because it can be obtained by combining results from multiple systems). Therefore, 126 different combinations of the work order characteristics were used to create the testing work order contexts.

The efficiency of reducing the search space for applicable components for different work order contexts is presented in Table 12. The average efficiency rate is 68%, which means that the search space for listing the possible set of causes reduced by 68% and components and space related factors that are not relevant to a problem at hand are eliminated from the HVAC mechanics. The efficiency rates highly depend on the type of reported problems. For example, temperature problem has the largest number of components being applicable, while humidity problem has the smallest number of components being applicable, and hence temperature problem has the lowest efficiency rate and humidity problem has the highest.

Table 12. Efficiency of search space reduction for different work order contexts

Problem type	**Spatial scope**	**Testbeds**							
		1	2	3	4	5	**6**	**7**	**Average**
Temperature	Single zone	64%	63%	61%	56%	78%	25%	17%	**49%**
Temperature	Multiple-zone/single system	60%	64%	64%	67%	45%	14%	9%	
Air flow	Single zone	77%	69%	72%	63%	78%	100%	33%	**71%**
Air flow	Multiple-zone/single system	67%	82%	80%	76%	73%	100%	27%	
Humidity	Single zone	82%	81%	78%	63%	78%	100%	100%	**85%**
Humidity	Multiple-zone/single system	87%	86%	84%	71%	82%	100%	100%	

Odor	Single zone	91%	88%	83%	81%	94%	100%	50%	**76%**
Odor	Multiple-zone/single system	70%	73%	72%	62%	59%	100%	45%	
Water leak	Single zone	77%	81%	83%	81%	64%	25%	50%	**65%**
Water leak	Multiple-zone/single system	70%	77%	80%	76%	64%	29%	55%	
Noise	Single zone	73%	69%	72%	63%	83%	50%	50%	**63%**
Noise	Multiple-zone/single system	63%	59%	64%	57%	73%	57%	55%	
Average		**73%**	**74%**	**75%**	**68%**	**73%**	**67%**	**49%**	**68%**

The results of the tests show that the precision for all tests are 100%, which means all the identified causes for different combinations of the work order characteristics are real applicable causes and all applicable causes were retrieved. The testbeds (i.e., Testbeds 1, 4 and 5) that contain special space and HVAC configurations have cases of false negatives (i.e., identified as inapplicable, but actually is applicable cause for a given work order), which lowered the recall rates as shown in Table 13.

Table 13. Recall rates for different work order contexts

Problem type	**Spatial scope**	**Testbeds**						
		1	2	3	4	5	6	7
Temperature	Single zone	100%	100%	100%	100%	100%	100%	100%
Temperature	Multiple-zone/single system	100%	100%	100%	**78%**	**67%**	100%	100%
Air flow	Single zone	100%	100%	100%	100%	100%	100%	100%
Air flow	Multiple-zone/single system	100%	100%	100%	**60%**	**60%**	100%	100%
Humidity	Single	100%	100%	100%	**75%**	**75%**	100%	100%

	zone							
Humidity	Multiple-zone/single system	100%	100%	100%	**75%**	**75%**	100%	100%
Odor	Single zone	100%	100%	100%	100%	100%	100%	100%
Odor	Multiple-zone/single system	**75%**	100%	100%	**86%**	**78%**	100%	100%
Water leak	Single zone	100%	100%	100%	100%	100%	100%	100%
Water leak	Multiple-zone/single system	100%	100%	100%	100%	100%	100%	100%
Noise	Single zone	100%	100%	100%	100%	100%	100%	100%
Noise	Multiple-zone/single system	100%	100%	100%	100%	100%	100%	100%
Average		**98%**	**100%**	**100%**	**90%**	**88%**	**100%**	**100%**

These false negatives in the recall rates were analyzed to understand the boundaries of the reasoning mechanisms. For Testbed 1, the false negatives were happened when a work order was generated for an odor problem in the cluster. The applicable HVAC components that were not identified are an exhaust fan and an exhaust air damper which serve the lab space next to the cluster. The components were not identified because they do not directly serve the given room thus do not exist in the return/exhaust graphs traced by the algorithm. The exhaust fan and damper would be considered as applicable because lab space is very likely to be the source of odor problem, and if the exhaust system in the lab space was not functioning properly, the odor can travel to nearby rooms through the open space. The developed approach will not be able to identify causes for odor problem that can travel through building pathways.

Regarding the false negatives in Testbed 4, a central exhaust fan and an exhaust damper were also not identified for temperature, air flow, humidity and odor problem in multiple zones. This is caused because the exhaust fan and damper were not correctly identified as components in central system when not all spaces in the system are connected with the exhaust system. This type of design was not observed in ASHRAE handbook (2008), and it could be due to the attempt to reduce the duct lengths, but could cause pressurization problems in the rooms which do not have clear return/exhaust path (Burdick 2011). According to the algorithm of *HVAC Graph Generato*r, the components that are shared by all spaces will be labeled as component in central system. When a problem happens in multiple zones, applicable components in the central system will be retrieved. However, the exhaust fan and damper are not shared by all spaces in the system because there are spaces not connected with the central exhaust system. This case shows that the developed approach works better for HVAC systems conforms to the design requirements and constraints described in ASHRAE handbook.

Similarly, regarding the false negatives in Testbed 5, all HVAC components in the return/exhaust system were not identified because the system uses ceiling plenum for the return air circulation from the spaces, instead of traditional ductwork. Because there are no physical connections between the spaces and return/exhaust system, the algorithm was not able to trace the return/exhaust route to find the components. This shows that the developed approach works better for HVAC systems that have physical connections among the HVAC components.

Given these results, it is important to note that the approach works best for HVAC systems that conform to the design requirements and constraints described in ASHRAE handbook, and for HVAC systems that do not use ceiling plenums for air return. This approach has limitations in identifying causes for odor problems travelling through building pathways. However, in general, the results show that both precision (100%) and recall are high (88% - 100%), which means that the system performs well in identifying applicable causes for work orders generated under different contexts and different standard HVAC configurations.

3.4 Conclusions

This chapter presents an automated approach to identify applicable causes and retrieve required information for a given work order to streamline the process of troubleshooting HVAC related problems. The contribution of this study includes (a) representation schema that enables integrated representation of HVAC troubleshooting related information, that are typically stored in BIM, BAS, CMMS, and design documents, (b) algorithms that generate a work order's context through a graph-based reasoning and standard HVAC design constraints, identify applicable causes and match them to facility specific instances through functional differentiation of HVAC components in order to rectify a given problem.

The approach was validated in terms of its *efficiency* and *accuracy* to identify applicable causes for different work order contexts generated for different types of HVAC systems. The results showed that the approach was able to reduce the search space of applicable causes by 68% on the average and achieved high precision and recall rate regardless of the work order contexts used. While the precision is 100%, the recall drops in cases when the HVAC systems do not conform to the standard design practices and constraints described in ASHRAE handbook. This approach can help HVAC mechanics to pinpoint the right set of causes for a given HVAC related problem causes, so that they don't miss the root cause or waste time on tracing and locating components on field. The approach also provides the required information about these causes promptly, so that HVAC mechanics can have sufficient information support to diagnose the real cause.

Chapter 4. Development and evaluation of an integrated information visualization platform to support troubleshooting of HVAC related problems

Visualization can enhance human's perception and comprehension of information, and visualization has been successfully used for various Architecture Engineering Construction and Facilities Management (AEC/FM) tasks, such as design review (Yerrapathruni 2003; Gopinath & Messner 2004; Leicht et al. 2010; Majumdar et al. 2006; Messner 2006; Dunston et al. 2007), construction management (Roh et al. 2011; Song et al. 2005), facility operation monitoring (Kim et al. 2012; Schulze 2010), and facility maintenance (Akcamete 2011; Su et al. 2011; Sampaio et al. 2009). In order to understand the impacts of different visualization techniques on HVAC mechanics' comprehension of information, I first picked one data source – the data from building automation systems, developed various design options to display the data, and evaluated the different options by measuring the accuracy and efficiency of completing assigned tasks by HVAC mechanics. The details of this initial study are provided in section 4.2. The findings from this study show that the best visualization-based interfaces saved more than 50% of the time while improve accuracy rate by 15% averagely for facility operators, compared with using interfaces with tabular format. This study only used BAS data as the information source, and BAS data is only one of data sources that are needed for HVAC mechanics to troubleshoot HVAC related problems. Hence, I further explored the visualization techniques for other information required by HVAC mechanics, and conducted user studies to evaluate the efficiency improvement achieved by visualization, which is presented in section 4.3.

4.1 Background research

4.1.1 Integration of scientific visualization with information visualization

Visualization, which transforms data, information and knowledge into visual forms that enable human brain to get the perception easily, is able to enhance human's capability and efficiency of dealing with complex or large volume of data (Gershon et al. 1998). In general, visualization techniques can be grouped under two categories, as scientific and information visualization (Card et al. 1998). The idea with the scientific visualization is that the focus is on displaying physical and tangible objects (such as walls and windows) whereas in information visualization the focus is on displaying abstract and intangible data sets (such as sensor readings). A large number of previous research studies on visualization in the AEC domain focused on visualizing building product and process models, more specifically on using 3D or 4D virtual prototypes to enhance the communication in design review processes (Savioja et al. 2003; Gopinath & Messner 2004; Majumdar et al. 2006; Dunston et al. 2007; Leicht et al. 2010; Whiskschder et al. 2003; Maldovan & Messner 2006; Messner 2006). Such studies mainly fall under the scientific visualization category. Majority of the research studies done on visualization within the Human Computer Interaction (HCI) domain focused on displaying datase - especially multi-dimensional, hierarchical or complex ones (Keim & Kriegel 1996; Shneiderman 1996; Keim 2002; Pfitzner & Hobbs 2003; Qin et al. 2003), which mainly fall under the information visualization category.

The required information for troubleshooting of HVAC related problems enbrace both tangible objects (e.g., HVAC components) and their locations, and intangible data (e.g., sensor readings), and thus display of such information requires the integration of scientific and information visualization. This integration basically enables encoding semantic information in spatial context.

Therefore, while reviewing the previous research studies on visualization, I focused on the studies that integrated the two categories with an emphasis on the AEC/FM and HCI domains.

4.1.2 Visualization in Architectural/Engineering/Construction (AEC) domain

In the AEC/FM domain, various visualization techniques were used to support construction management. Color coding has been the most widely used visualization technique to encode semantic information in 2D (e.g., on site/floor plans) and 3D settings (e.g., building information models, geography) for different purposes, such as construction progress monitoring (Roh et al. 2011; Song et al. 2005), construction field surface movement monitoring (Hsieh & Lu 2012), construction workspace and logistics management (Sjödin & Boström 2011; Elmahdi & Wu 2011), and safety management (Cheng & Teizer 2013). Besides color coding, Song et al. (2005) altered visual attributes on the faces, edges, or shapes of building components in 3D view to display multi-dimensional construction project datasets in a single view, Hsieh & Lu (2012) used the size of virtual geometrical primitives (e.g. sphere, cube, cylinder) to encode sensor readings, and Cheng & Teizer (2013) used text annotation in virtual reality to display the distances between construction workers and cranes. In addition, Augmented Reality (AR) is a visualization technology that superimposes digital information on real world scenes (Shin & Jang 2009, and has been explored a lot for construction management. There have been research studies that augmented 3D virtual objects (e.g., buildings or construction equipment) on construction sites (Behzadan 2008; Behzadan & Kamat 2005; Woodward et al. 2010) to support site selection and management, which can also be grouped as scientific visualization since only 3D objects were visualized. AR has also been used for construction progress monitoring, in which color coded virtual building elements were superimposed on site photographs to show construction schedule statuses (Golparvar-Fard & Peña-Mora 2007; Golparvar-Fard et al. 2009).

4.1.3 Visualization in Facilities Management (FM) domain

There have been research studies that leveraged visualization for facilities management as well. A similar trend of using color coding on 3D views of building components has been observed. For example, Su et al. (2011) and Sampaio et al. (2009) used this technique to display facility maintenance statuses. Besides color coding, previous research studies utilized symbols and text overlays as well. For example, Akcamete (2011) integrated work order information with BIM and visualized work order frequency in spaces using different colors and symbols, and used text overlays to show the number of work orders that were issued for each space. In addition, AR has been a widely used approach for visualization of information within spatial context so that information can be retrieved on field for facility maintenance staffs (Lee et al, 2011; Irizarry et al. 2011; Shen & Jiang 2012).

In terms of facility monitoring, similar to greenhouse facilities, data centers and physical plants require close monitoring of operation conditions as well. Similar information visualization approaches were used to display information for such facilities, such as displaying power consumption and temperature distribution in a data center Schulze (2010) and a physical plant Einsfeld et al. (2008). There have been also research studies that focused on visualizing building energy use, which incorporated dashboard-like interfaces with different types of charts to show vital building energy related information to facility operators and occupants (Granderson et al. 2009; Lehrer 2009a, 2009b; Lehrer & Vasudev 2010), but geometrical and spatial information visualization are typically not involved in these studies. In a similar context, Kim et al. (2012) developed a visualization system for a green city, and the system was capable of displaying energy related information for a city by using color coding, text annotation, and charts in a single interface with multiple views.

There are also research studies that focused more from the perspective of visualization and visual analytics for FM purposes, which enable analytical deductions through the use of visualization. As building information models (BIM) gained momentum for use in the industry to store and exchange facility information, recent studies have mainly built on BIM's visualization capabilities to display facility information (e.g., Motamedi et al. 2014; Akcamete 2011; Chen et al. 2013; Su et al. 2011 and Lin and Su 2013). Such studies use visualization to help facility operators to identify reasons of failures in buildings, keep track of the changes in facilities due to maintenance, and get access to facility maintenance information. Since BIM has its intrinsic characteristic of having geometric information being represented in 3D, majority of the research studies in this group used 3D model as the only interface to display facility information with a limited exploration of the other possible ways to display the same information. Regarding the visualization of semantic information, however, color-coding, where a spectrum of colors are used to show scalar values, has been the most commonly used technique to augment 3D model with semantic information (e.g., Sampaio et al. 2009). In such studies, typically building components are color-coded to display scalar values of attributes of these components. Additional techniques of using symbols/metaphors, where categorical information is embedded in 3D views using symbols and metaphors, and text overlays, where metadata about components are shown in textboxes, for augmenting 3D component information have also been observed (e.g., Golparvard-Fard et al. 2009, Song et al. 2005). All of the research studies took 3D models for granted as the best visualization interface and augment semantic information on 3D models. However, a recent study done on evaluating different visualization techniques for facility operators suggests that 3D-based visualization is not always the best way to display facility information (Yang and Ergan 2014c). Hence, previous research studies showed scarcity in looking at different ways of visualizing facility information, and there is a research gap in the literature to understand the impact of visualization on the perceptions of HVAC mechanics in conceiving the troubleshooting information.

4.1.4 Methods to develop and evaluate visualization environments for AEC/FM

A large number of research studies in visualization for AEC/FM focused on developing 3D/4D models or virtual environments, generation of computer simulations that simulate physical presence in imagined worlds to get visual experiences (Bartle 2003), for design review and preconstruction planning (Yerrapathruni 2003; Gopinath & Messner 2004; Leicht et al. 2010; Majumdar et al. 2006; Messner 2006; Dunston et al. 2007). While 3D/4D and virtual environments have been widely explored and accepted in both academia as well as in the industry to visualize geometric and spatial data, the visualization of abstract, non-spatial data for AEC/FM still has limited emphasis on it (Russell et al. 2009).

Unlike many commercial and open-source tools available to create 3D/4D models and virtual environments, the development process and the useful visual solutions for displaying abstract data are also less well-defined. An iterative design process is effective when developing new visual representations, which has been successfully used by various researchers before (e.g., Russell et al. 2009 and Lee and Rojas 2013) to develop visual representations for construction management. Iterative design process is the fundamental concept in usability engineering in Human-Computer-Interaction (HCI) domain (Nielsen 1994). In iterative design process, the end users are included in the early design stage and their feedbacks are used to improve the visual design of proposed solutions. Low-fidelity prototyping is usually first used to quickly get users' feedbacks at early stages with low cost, and then high-fidelity prototyping is used to implement the final design products that take into account users' feedbacks (Rettig 1994).

The evaluation methods used for visualization environments typically include user tests. Studies have used quantitate or qualitative metrics to measure the effectiveness of visualization environments. Common quantitative evaluation metrics include the measurement of time it took for users to complete given tasks, and the measurement of the accuracy of the decisions in completed tasks (e.g., Hsieh and Lu 2012; Kuo et al. 2011; Yang and Ergan 2014c). Qualitative evaluation metrics, such as users' preferences and options, are also valuable to understand the metal efforts for users to interpret the visualization interfaces (Huang et al. 2009; Russell et al. 2009; Esp ńdola et al. 2013, Yang and Ergan 2014c).

The study presented in this chapter also used an iterative design process to develop the required visualization environment to provide information support for HVAC mechanics, and both qualitative and quantitative metrics were used in the user studies to evaluate the visualization interfaces.

4.1.5 Visualization in Human Computer Interaction (HCI) domain

In the HCI domain, previous research studies have explored integrating the power of virtual environment with information visualization, i.e., developing information-rich virtual environments (Bowman et al. 2003) that build the link between perceptual environment and the related abstract information (Bowman et al. 1998, Bowman et al. 2003). Information-rich virtual environments are used to integrate scientific and information visualization; however, scrutiny into these studies shows that that the techniques of displaying semantic information in virtual environment are limited to superimposing text onto related objects (Bowman et al. 1998; Polys & Bowman 2004; Polys et al. 2007; Poly et al. 2004).

4.1.6 Synthesis of previous research studies: encoding semantic information in spatial contexts

Review of previous studies in the AEC/FM and HCI domains showed that the common visualization techniques for displaying spatial/geometrical information in the AEC/FM domain include 2D floor plans (e.g., Elmahdi et al. 2012), site maps/plans (e.g., Fan and Biagioni 2004), geospatial maps (e.g., Kim et al. 2012), and 3D models (e.g., Hsieh and Lu 2012). In the HVAC domain, schematic diagrams (ASHRAE 2008) represent the most commonly used visualization technique to show the configurations of HVAC systems and topological relationships among HVAC components. Related ASHRAE handbooks (handbook 2009) also use block diagrams, which provide the main functions and relations between the functions as a combination of boxes and lines, to show the control relationships of HVAC components.

On the other hand, the visualization techniques for semantic information are various. It is observed from literature that semantic information that needs visualization can be grouped into two categories: 1) Semantic information that has large, complex or hierarchical data sets that represent a high-dimensional nature (Shneiderman 1996). This type of semantic information does not associate with tangible objects- hence typically not integrated with scientific visualization, and can be visualized by standalone charts, graphs or diagrams, such as tree maps (Shneiderman 2006), parallel coordinates (Wegman 1990), and scatterplot matrices (Touchette et al. 1985). 2) Semantic information that is associated with tangible objects (hence with spatial or geometrical information of objects). For example, sensor readings with respect to spatial distribution of sensors (Hsieh and Lu 2012). In such a case, the visualization of semantic information needs to be integrated with the visualization techniques for spatial/geometrical information. The required information for HVAC mechanics for troubleshooting belong to this category because it includes both tangible objects and spatial information, such as HVAC components' location, and their associated semantic information as intangible data, such as parameter readings and maintenance history.

Tauscher et al. (2011) defines three categories of visualization techniques to aggregate abstract information in product models: visualization by blending, visualization by embedding and visualization by interaction. Blending means mapping of semantic information to the visual attributes (such as color, size or position) of objects; embedding means displaying semantic information in secondary views (e.g., as text/number overlays, or annotations) in a host environment; and visualization by interaction means connecting multiple views through users' interactions and capturing interactions in one view to trigger visual efforts (e.g., highlighting) in another view. The name of visualization by interaction can be misleading because blending or embedding can also be triggered by user's interaction, and thus it will be referred as visualization by multi-viewing in this study. These three categories provide a high-level taxonomy of visualization techniques to integrate scientific and information visualization, and visualization techniques used in other research studies can be grouped under these three categories. Table 14 provides the detailed classification of visualization techniques that are used to encode semantic information in spatial contexts. Visualization techniques including color coding, pattern coding, and animation directly modify the visual attributes of objects, and thus can be grouped under visualization by blending. Symbol/metaphor, text overlay/annotation and chart overlays are the techniques that create additional views or objects in the original host view, and thus they fall under visualization by embedding group. Multi-viewing can be a combination of various types of views with different visualization techniques and thus do not have specific sub-categories.

Table 14. Classification of visualization techniques to encode semantic information in spatial contexts

Categories	**Applicable visualization techniques**	**Type of encoded semantic information**	**Visualization for multiple objects or single object**	**Previous studies that used the visualization techniques**
Blending	Color coding	Categorical; Scalar	Multiple objects	Song et al. (2005); Roh et al. (2011); Liston & Fischer (2000); Hsieh & Lu (2012); Kim et al. (2012); Elmahdi et al. (2011); Hammad & Motamedi (2007); Sampaio et al. (2009a); Sampaio et al. (2009b); Akcamete et al. (2011); Schulze (2010); ElHakim & ElHelw (2010); Golparvar-Fard & Peña-Mora (2007); Golparvar-Fard et al. (2009); Einsfeld et al. (2008)
	Pattern coding	Categorical	Multiple objects	Roh et al. (2011)
	Animation	Spatial-temporal (construction schedule)	Multiple objects	Huang & Kong (2007); Gopinath & Messner (2004); Maldovan & Messner (2006); Doulis & Vogel (2007)
Embedding	Symbol/ metaphor	Categorical; Scalar	Multiple objects	Hsieh & Lu (2012); Fan & Biagioni (2004); Akcamete et al. (2011); Einsfeld et al. (2008)
	Text overlay /annotation	Categorical; Scalar; Descriptive	Single object; Multiple objects	Liston & Fischer (2000); Huang et al. (2007); Lee (2009); Kim & Shin (2012); Kim et al. (2012); Bowman et al. (2003); Schulze (2010); Bowman et al. (1998); Cheng & Teizer (2013); Irizarry et al. (2011); Shen & Jiang (2012)
	Chart overlay	Temporal (time-series data)	Single object; Multiple objects	Akcamete et al. (2011); Rohr et al. (2008); Kim et al. (2012)
Multi-viewing	N/A	Various types of data	Multiple objects	Kuo et al. (2011); Kubicki et al. (2007); Kim et al. (2012)

As shown in Table 14, color coding, pattern coding and symbol/metaphor are typically used for encoding categorical data, which represents data that can be grouped into categories, such as On Schedule, Ahead of Schedule, or Behind Schedule for construction progress (Roh et al. 2011), Satisfactory, Unsatisfactory, or Delayed for facility maintenance results (Sampaio et al. 2009b). These different categories of data can be encoded by different colors/patterns on their associated components, or by symbols or metaphors, such as icons (Fan and Biagioni 2004) or geometrical primitives (Hsieh and Lu 2012). Color coding is also applicable for scalar data, which represents data that has a quantity. For example, spectrums have been used to indicate a range of values, such as the number of work orders issued in a space (Akcamete et al. 2011) (Figure 17.1), and sensor readings in spaces (Hsieh and Lu 2012) (Figure 17.2).

Figure 17.1 Spectrum to show work order number (Akcamete et al. 2011)

Figure 17.2 Spectrum to show sensor readings (Hsieh and Lu 2012)

In addition, temporal data, which represents data that has time dimension associated with it, is commonly visualized by animations or time-series charts. Animation is widely used to visualize construction schedule integrated with 3D building model, known as 4D. Animation is a powerful visualization technique when users need to know the progress of an event and the spatial-temporal information. When users want to know the patterns of data in a specific time frame, time-series chart is more intuitive (Hsieh & Lu 2012). At last, text annotation/overlay is commonly used to show descriptive data, which is usually a text box put next to the associated component to indicate the component's properties that are important to the users. Text annotation/overlaying is a very general technique for encoding information in spatial contexts, and has been thoroughly studied in generating information-rich virtual environments (Bowman et al. 2003; Schulze 2010; Bowman et al. 1998). It is also the very basic technique used in AR to superimpose information in physical settings. The content put in a text box generally kept succinct to eliminate the blockage of the host view.

The visualization techniques are also analyzed regarding to their applicability to multiple objects or a single object at a given time. It was found that in all of the reviewed previous studies, color/pattern coding, animation, symbol/metaphor and multi-viewing techniques are all associated with multiple objects at a given time, as they require a spectrum of values to generate meaningful displays. For example, the color coding technique was used to visualize maintenance results for multiple facility components (Su et al. 2011); an animation was used to display the process of constructing various building elements in a chronological order (Gopinath and Messner 2004); and the virtual metaphor technique was used to visualize multiple sensor readings (Yang and Ergan 2014). The intentions of using color/pattern coding and symbol/metaphor are to enable users to compare a common aspect of a set of components in order to identify the components that outstand given the spectrum (e.g., to identify facility components with unsatisfactory maintenance status, and sensors out of thresholds). Therefore, to effectively use the techniques of color/pattern coding and symbols/metaphors, a common property should exist for the components interest for visualization. On the other hand, chart overlays and text overlays/annotations are generally used to show semantic information for a specific component or multiple components of interest.

The visualization techniques that encode semantic information in spatial contexts as summarized in Table 14 were used in this study to identify applicable visualization techniques for different information items.

4.2 Evaluation of visualization techniques for use by facility operators during monitoring tasks

Modern building automation systems (BASs) using direct digital control (DDC) not only provide automatic control of indoor environments, but also allow remote monitoring and control for facility operators. Real-time monitoring of BASs' operational conditions is fundamental to ensure prompt response to abnormal situations in a facility (Burns 2005). However, modern sophisticated BASs sometimes surpass the facility operators' capability to manage them (Burns 2005). It is found that human factors, including operator errors, unawareness, interferences, and indifferences, are one of the most important factors that lead to system control problems, and that accounts for 29% of all problems in BASs control (Barwig et al. 2002). Therefore, it is important that the interfaces that facility operators use are designed in such a way that they enhance facility operators' situation awareness on operational conditions and minimize operator errors when interacting with BASs.

This research study was motivated by a case study that was conducted in a greenhouse facility. We have conducted interviews, shadowing and contextual inquiries, during which we explored the way facility operators use BASs in their daily routines. Interfaces of BASs in greenhouse facilities are even more important than those designed for regular commercial buildings because they require more frequent monitoring to ensure that the plants are in healthy conditions at all times. In the case study, I also evaluated the interface of the BAS that is currently in use at the greenhouse facility, together with a sample set of BASs used in other greenhouse facilities or regular buildings. These BASs were selected from the industry as well as the ones that were described in details in previous research studies. It was identified from the evaluations that there are two main issues with the way information is provided to facility operators: (1) lack of spatial context for sensor readings and equipment statuses and (2) information overloading, which reduced the efficiency and accuracy of facility operators' decisions to perform their daily monitoring tasks. Both of these challenges indicate a need for environments which can provide spatial context of sensor readings and equipment statuses while minimizing information overloading for facility monitoring tasks.

Visualization is known to improve human's perception and efficiency of dealing with complex and/or large volumes of data (Gershon et al. 1998). Various visualization techniques have successfully been used by previous research studies to support different monitoring tasks, such as monitoring of construction fields (e.g., Hsieh & Lu 2012), data centers (e.g., Schulze 2010), energy use in cities (e.g., Kim et al.), and sensor networks (e.g., ElHakim & ElHelw 2010; Fidaleo et al. 2004; Rohr et al. 2008; Fan & Biagioni 2004). The study presented in this chapter builds on this premise that human's perception and efficiency change with the way information is presented to them and hypothesizes that visualization techniques that are used to display necessary information in facilities could enhance facility operators' accuracy and efficiency during their daily monitoring tasks.

In order to test this hypothesis, I conducted an extensive review of visualization techniques that have been used in previous research studies, with an emphasis on the ones that merge semantic information with spatial information, due to the need of relating sensor and equipment status information to the space information. Information needed by facility operators during typical monitoring tasks in their daily routines was identified and used as a baseline to evaluate the impact of different visualization techniques in facility operators' perception, responses and accuracy of their decisions. I used low-fidelity prototyping method (Retting 1994) to implement the visualization-based interfaces. Low-fidelity prototyping method has been adopted in this research study because of its effectiveness of getting end user's feedbacks with low development cost, quick turnaround time and iterations of multiple design options (Retting 1994; Rudd et al. 1996). A detailed explanation of how these low-fidelity prototypes have been used in the study is provided in Section 4. Two quantitative metrics - accuracy rate and time of completing the tasks using different interfaces, and one qualitative metric – users' preferences, were used for the evaluation. This chapter section provides a detailed description of the case study, the challenges faced by facility operators while monitoring indoor environments, the design and the results of the user tests performed with various facility operators from two different facilities management groups and graduate students of Civil and Environmental Engineering department.

4.2.1 Equipment monitoring in a greenhouse facility and challenges faced by facility operators while interacting with BAS interfaces

This work has been motivated by a case study that was conducted in a highly sensed greenhouse facility, which encompassed 12000 square feet. It was designed with a curved south glass wall and sloped glass roof to allow enough natural light for tropical plants and minimize energy consumption for heating in winter. The objective of the case study was to understand the monitoring process in the facility, observe facility operators' interactions with the BAS, and understand how the BASs help facility operators during their daily routines. I shadowed a facility operator once in a week for three consecutive months to understand facility operators' daily routines in monitoring indoor environment requirements.

In the greenhouse facility, the core controlled indoor environment parameters were the temperature and humidity for tropical plants. Due to the large square footage and high ceiling (i.e., 60 feet) of the facility, the indoor space was divided into 5 zones and each zone had one lower sensor (on the ground) and one upper sensor (on the ceiling) measuring temperature and humidity. Figure 18a is a picture of the zone and sensor map that was used by the facility operators. This map shows the zones of the facility (i.e., Zone 1, Zone 2, Zone 3A, Zone 3B and Zone 4) and the locations of the upper/ lower level sensors for each zone with green/red square icons. The BAS took temperature and humidity readings from the sensors and controlled the equipment to adjust the parameters in a pre-defined ideal range, which was set as 62 ℉ - 68 ℉ for temperature and 60 % – 90% RH (relative humidity) for humidity.

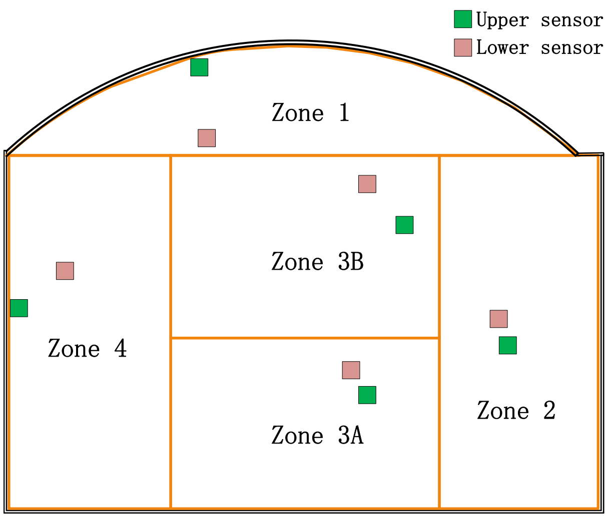


Figure 18a. Zone and sensor map

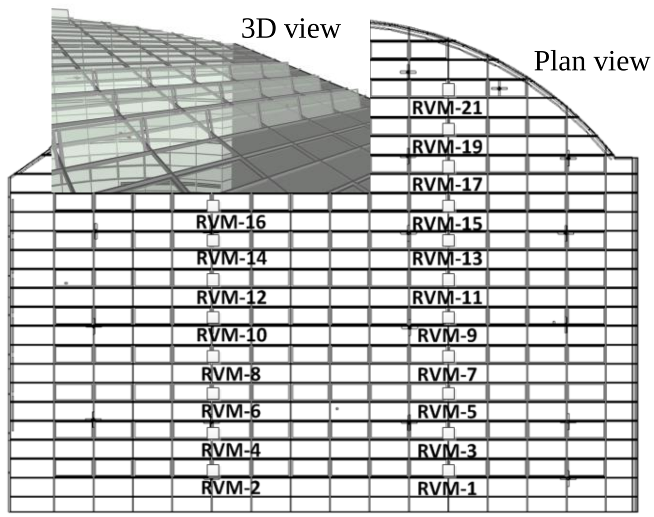


Figure 18b. Locations of roof vent motors (RVM)

Figure 18. The greenhouse facility zones, sensors and controlled roof vent motors

In terms of the equipment used to control temperature and humidity, the facility used 100% natural ventilation and passive cooling, hence had no mechanical heating ventilation and air conditioning (HVAC) system such as air handling unit (AHU) for ventilation or cooling. This resulted in having the facility operators control a different set of equipment than usual HVAC equipment. Ventilation and cooling has been achieved by operating vents in the roof. Figure 18b shows the locations of the roof vent motors and their IDs along with a zoomed in picture of a row of vents. Heating in the winter is achieved by fin tubes which use steam as the heating source. For humidity control, the vents are used to dehumidify and there are fogging lines that could be used to add humidity.

On a typical day, facility operators in the greenhouse facility would monitor current readings about indoor temperature and humidity measured by sensors in five different zones. Facility operators would need to know if the parameters (i.e., temperature and humidity) were within the ideal range or not. If the parameters were out of the ideal range, they would need to find out the reason behind the abnormal readings and check whether the BAS took the necessary actions to adjust the parameters. A unique requirement in greenhouse facilities is the need for closer and more frequent monitoring of controlled parameters by facility operators as compared to that in residential and commercial buildings. The need for a closer and more frequent monitoring is to capture the changes in the ambient measurements that could affect the plants' health conditions as plants cannot actively help raise these issues as occupants do.

The BAS of this specific greenhouse facility allowed facility operators to remotely monitor and control the spaces through a user interface, as shown in Figure 19. Specifically, 2a and 2b show the BAS interface of displaying sensor data and controlled equipment statuses, respectively. In Figure 19a, the left and right columns show the sensor names and their readings at a point in time, respectively. The sensors are named based on the zones where they are located at. Temperature readings are in Fahrenheit (°F) and humidity readings are in Relative Humidity (%RH). In Figure 19b, the left column shows equipment ID and the right column shows their current operation and control status.

Upper RH Sensor 3A	67.0	%RH
Upper °T Sensor 3A	67.7	°F
Lower RH Sensor 3A	98.0	%RH
Lower °T Sensor 3A	65.8	°F
Upper RH Sensor 3B	75.3	%RH
Upper °T Sensor 3B	67.4	°F
Lower RH Sensor 3B	77.1	%RH
Lower °T Sensor 3B	63.7	°F
Upper RH Sensor 1	66.9	%RH
Upper °T Sensor 1	67.8	°F
Lower RH Sensor 1	99.0	%RH
Lower °T Sensor 1	62.6	°F
Upper RH Sensor 2	60.3	%RH
Upper °T Sensor 2	60.9	°F
Lower RH Sensor 2	65.0	%RH
Lower °T Sensor 2	65.4	°F
Upper RH Sensor 4	67.0	%RH
Upper °T Sensor 4	59.7	°F
Lower RH Sensor 4	68.0	%RH
Lower °T Sensor 4	65.8	°F

RVM-1, 2	Position at	0
RVM-3, 4, 5, 6	Position at	0
RVM-7 to 12	Position at	0
RVM-13, 15	Position at	0
RVM-14, 16	Position at	0
RVM-17, 19	Position at	0
RVM-18, 20	Automatic	0
RVM-21	Automatic	100
RVM-22	Automatic	100
RVM-23	Automatic	100
Water Fall P1	Manual Off	
Water Fall P2	Manual Off	
SHM-SW Wall Shade	Automatic	0
SHM-S Wall Shade	Automatic	0
SHM-E Wall Shade	Automatic	0
SHM-SE Wall Shade	Automatic	0
SHM-2	Automatic	0
SHM-3	Automatic	0
SHM-5	Automatic	0

*Note: *0*: Vents are closed; *100*: Vents are open; *Position at*: equipment under manual control; *Automatic*: equipment under BAS control.

Figure 19a. Snapshots from the BAS interface showing the sensor data

Figure 19b. *Snapshots from the BAS interface showing the controlled equipment statuses

Figure 19. Snapshots from the BAS interface of the greenhouse facility

4.2.1.1 Challenges faced by the facility operators

Two main problems were identified during the observation of the facility operators' interactions with the BAS when they were monitoring the facility:

(1) Lack of spatial context

Locations of sensors and the controlled equipment were important for bringing spatial context to the operators to understand the closeness of sensors and equipment to the plants. With the current interface, the facility operators had to refer to external information sources, such as the sensor location map that showed the floor plan of the facility with sensors marked on it (see Figure 18a) and roof vents motor ceiling drawing that showed the location of the roof vent motors on the ceiling (see Figure 18b). They used the map and drawing to find out the ID of concerned sensor or roof vent motor based on their location, and then used the IDs to find the corresponding sensor readings and equipment statuses shown on BAS. The facility operator that I shadowed has been working in this greenhouse facility over seven years, was the main staff responsible for the operation of this facility, thus was very familiar with the system and memorized the maps over the years. However, it was observed that when these information sources were not readily available, other operators needed to spend extra time to recall the spatial context of sensors and equipment. There were still cases where a following visit to the space was necessary to make sure the right equipment was manipulated. For facility operators that were new to the facility, they needed to visit the site on a frequent basis and needed to check the maps to match the sensor and equipment IDs to their locations in the physical 3D space. Hence, the lack of spatial context in monitoring was exacerbated when new employees or other staffs were in charge. Therefore, interfaces should provide information about spatial context of sensors and controlled equipment for facility operators to easily relate the sensor readings and equipment statutes to their locations and their closeness to the content being monitored.

(2) Information overloading

Another important problem with the BAS interface in the greenhouse facility was that the interface showed the sensor readings and equipment statuses in purely tabular formats, as shown in Figure 19. The tabular format causes information overloading and is hard to interpret when there is a long list of sensors and equipment to monitor. Researchers pointed out that it is a challenge for facility operators in modern green house facilities to manage the large amount of data captured by BAS in a way that important information will not be neglected because of information overloading (Ehler and Aaslyng 2001). During the shadowing work, we found that several accidents had happened in the greenhouse facility because important information was not noticed. In one of the accidents, roof vent motors were malfunctioning and were not responding to the temperature and humidity requirements. The temperature kept increasing and reported to be more than 100 ℉ by the upper sensors. However, the operators did not notice such high temperature readings promptly and this caused damage to valuable tropical trees. In this case, facility operators needed a way to differentiate the abnormal sensor readings and recognize the operation statuses of roof vents at a glance. In another accident, one roof vent motor was under manual mode and was kept open for maintenance purposes, but the facility operator missed that the motor was still under manual mode when he was off work on a Friday. This accident resulted in the cancelation of an important event scheduled for that weekend because rain fell inside through the open roof vents (Yang & Ergan 2012). In this case, facility operators needed a way to recognize the control mode of roof vent motors at a glance. These examples suggest that facility operators need sensor readings and equipment's statuses in such a way that they can monitor and interpret the received data more easily without information overloading.

4.2.1.2 Evaluation of various BAS interfaces

To better understand the capabilities of the current BAS interfaces, I also explored interfaces of existing commercialized BASs, as well as the ones studied in previous research studies. A sample set of BAS interfaces that are utilized in greenhouse facilities and commercial buildings is shown in Figure 20 and Figure 21, respectively.

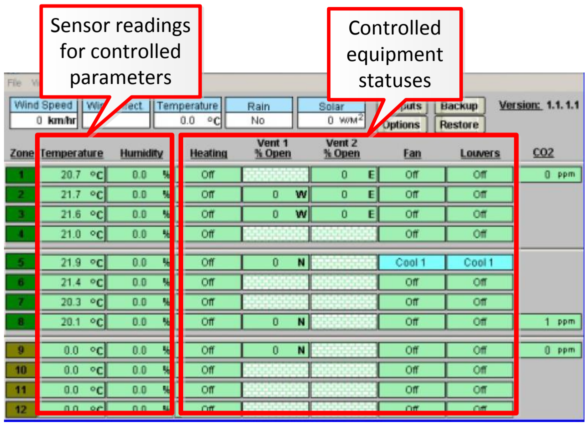


Figure 20a. Interface of BAS 1

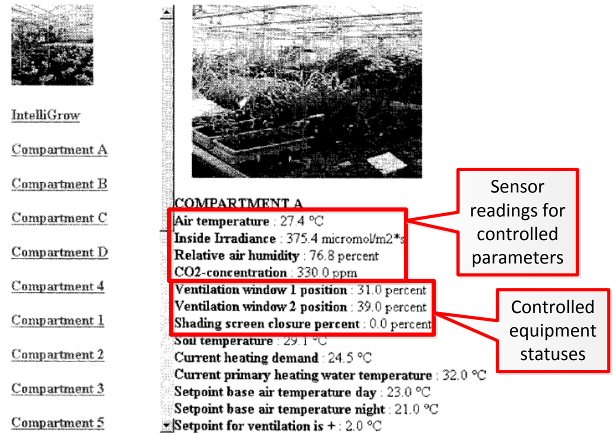


Figure 20b. Interface of BAS 2 (Ehler & Aaslyng 2001)

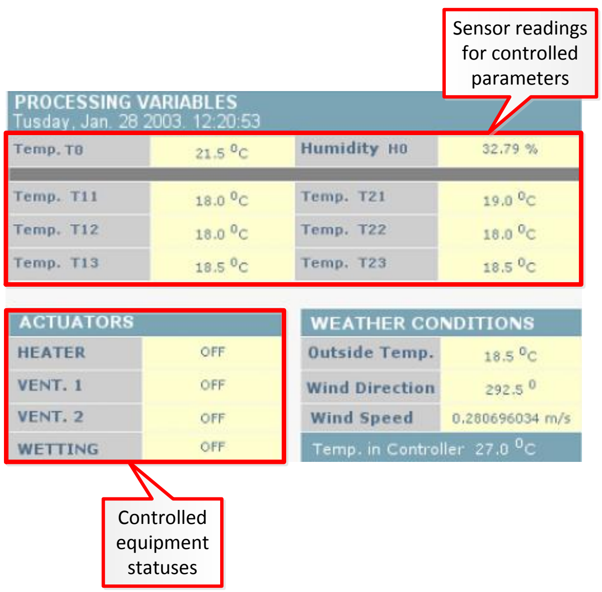


Figure 20c. Interface of BAS 3 (Stipanicev & Marasovic 2003)

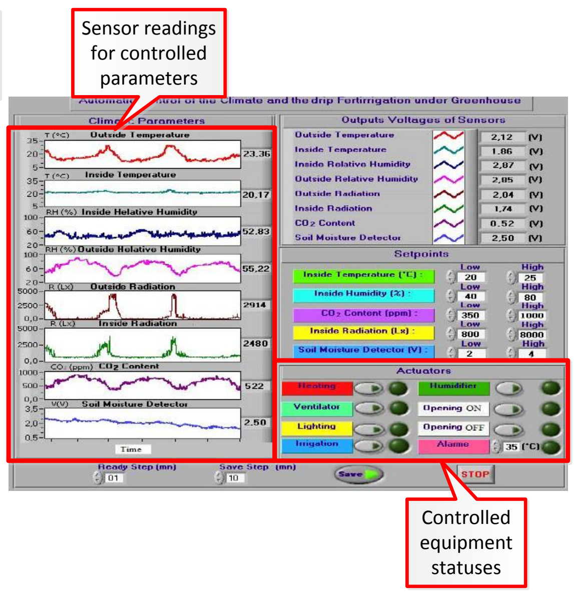


Figure 20d. Interface for BAS 4 (Rahali et al. 2011)

Figure 20. Sample set of BAS interfaces used for monitoring in greenhouse facilities

As shown in Figure 20, these interfaces also use tabular formats to show sensor readings and equipment statuses. Thus, similar challenges were observed to be applicable for these BAS interfaces. As discussed before, one characteristic of greenhouse facilities is that indoor climate in such facilities requires closer attention from facility operators as compared to commercial and residential buildings. Besides, greenhouse indoor climate is typically more dynamic and changes every few minutes (Ehler & Aaslyng 2001). Thus, it is important to make sensor readings and equipment statuses apparent and distinguishable for facility operators.

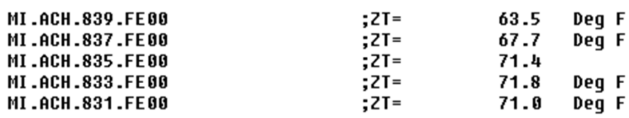


Figure 21a. Interface of BAS 5

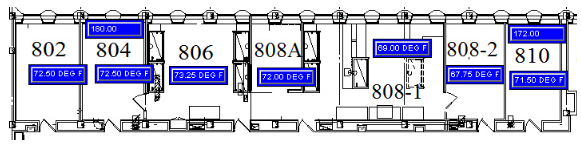


Figure 21b. Interface of BAS 6

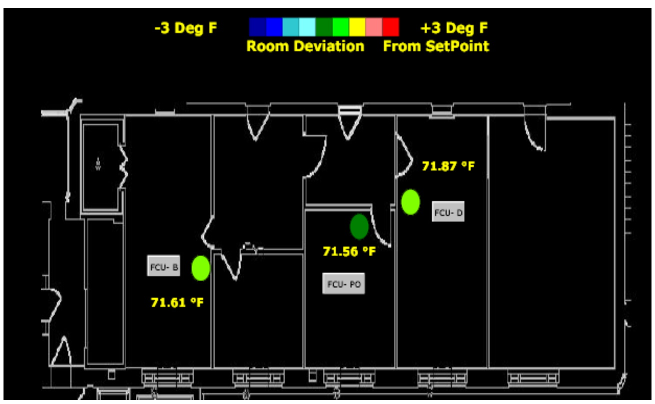


Figure 21c. Interface of BAS 7

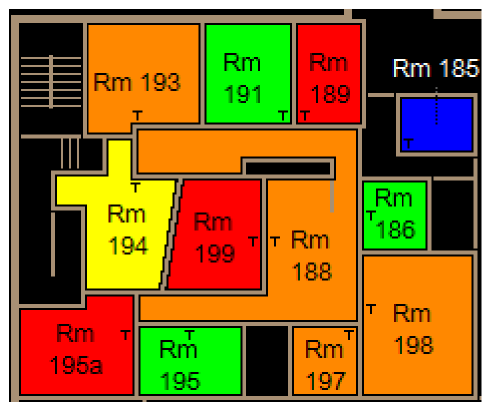


Figure 21d. Interface of BAS 8

Figure 21. Sample set of BAS interfaces used for regular commercial building monitoring

Regarding BASs used in regular commercial buildings, as shown in Figure 21, they have different interfaces to show space temperature sensor readings. What is different from the BASs in greenhouse facilities is that except BAS5 (Figure 21a), other BASs already started to use visualization techniques to encode temperature readings in floor plans. However the spatial context of equipment statuses is still an issue. In addition to this, it is unknown in the industry how these various types of visualization techniques affect the performance of facility operators during facility monitoring tasks. Hence, there is a need to understand the impact of visualization techniques used in these BASs on the performance of facility operators. To start with, I did an extensive literature review on existing visualization techniques that were used to encode semantic information within spatial settings, which is provided in the next section.

4.2.2 Research method

The objective of this research was to understand the impact of different visualization techniques on the accuracy and effectiveness of facility operators' decisions. Hence, to achieve this goal, I followed a three-prone approach: (1) direct observation and contextual inquiry to identify facility monitoring tasks and information used in these tasks, (2) identifying applicable visualization techniques for the required information, and (3) implementing low-fidelity prototypes to conduct user studies.

4.2.2.1 Direct observation and contextual inquiry

I did shadowing work with an experienced facility operator working in the greenhouse facility with the objective of understanding the routine monitoring tasks in the greenhouse facility and identifying any challenges faced by facility operators while using BASs. I shadowed the facility operator for a full day in each week for about three months. In the shadowing work, I followed the facility operator and directly observed his actions in relation to facility monitoring and did contextual inquiries where necessary. Contextual inquiry is a method of having discussions and conversations with subject matter experts under the context of their work (Beyer & Holtzblatt 1998), letting them "think aloud" in order to capture their tacit knowledge. As a result of these shadowing work and contextual inquiries, I identified two typical tasks within facility monitoring and identified the information the operators need during execution of these tasks. The identified tasks and information needed during the tasks are listed below (Yang and Ergan, 2012):

Task (1) *Situation awareness about the low temperature readings from the upper level sensors located under open roof vents in a winter day*. The upper level sensors typically have higher temperature readings than the lower level sensors in a given zone due to rising of warm air. However, since upper level sensors were mounted under the roof, they would have lower than normal temperature readings when the roof vents above these sensors were open in a winter day. By looking at the BAS interface given in Figure 19, the facility operators would need to (a) identify the abnormal temperature readings (i.e., readings that are out of the preset range) within the upper level sensor readings, (b) be aware of the operation statuses (i.e., open or close) of roof vent motors, (c) use the sensor map and equipment drawing to correlate the location of the upper sensors with that of the roof vents, and (d) decide if upper level sensors with low temperature readings are located under any open roof vents. If so, the low temperature readings would be considered as normal; if not, the readings would be considered as abnormal and would require further investigation.

Task (2) *Situation awareness about high humidity readings from sensors that are close to watered plants*. Tropical plants needed to be regularly watered, and when lower level sensors were close to the watered plants they could record very high humidity readings. Facility operators needed to (a) be aware of lower level sensor(s) with high humidity readings, (b) identify the ID of the zone where the plants were watered by using the sensor map, and (c) figure out if the lower level sensors with high humidity readings were located within the zone where the plants were just watered. If so, the high humidity readings would be considered as normal; if not, the readings would need to be treated as abnormal and would require further investigation.

The information required to do the tasks (1) and (2) is summarized in Table 15.

Table 15. Information needed by the greenhouse facility operators to complete the tasks

Task	Information needed to complete the task	Displayed on the current BAS interface?	Current display form on the BAS
(1)	Thresholds for the upper level sensors for temperature	Yes	Number description
	Temperature readings of the upper level sensors	Yes	Tabular format
	Location of upper level sensors relative to roof vents	No	N/A
	Operation statuses and control modes of RVMs	Yes	Tabular format
(2)	Thresholds for the lower level sensors for humidity	Yes	Number description
	Humidity readings of the lower level sensors	Yes	Tabular format
	Location of the lower level sensors relative to the watered zones	Yes	Tabular format

4.2.2.2 Identifying applicable visualization techniques for the required information

Using the information summarized in Table 15 and various visualization techniques identified from literature review (Table 14), I mapped the required information to the applicable visualization techniques and implemented different interfaces for facility operators' use. Required spatial information can be visualized by a 2D floor plan or a 3D building model, and various alternatives are available to encode the required semantic information of sensor readings and equipment statuses in spatial settings, as shown in Table 14. Sensor readings are scalar data, which can also be converted into categorical data using the preset ideal ranges and can be represented as Normal, Low, or High. Given categorical sensor readings, they can be visualized by color coding, symbol/metaphor or text overlay/annotations. Operation status (open or close) and control mode (manual or automatic) of RVMs are all categorical data, hence can be visualized by the same techniques. Visualization by multi-viewing is not considered as another design option, since once effective visualization environments are identified, a combination of these environments would form a multi-view interface. This resulted in having six options to display the required information to facility operators, as shown in Figure 22. Options 1.a to 1.c constitute 2D-based interfaces and options 2a-2c represent 3D-based interfaces.

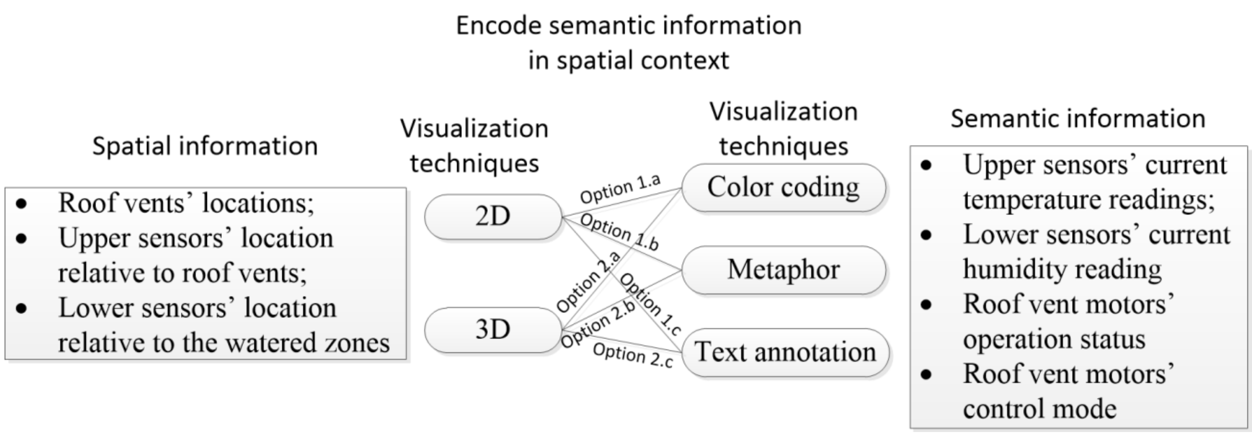
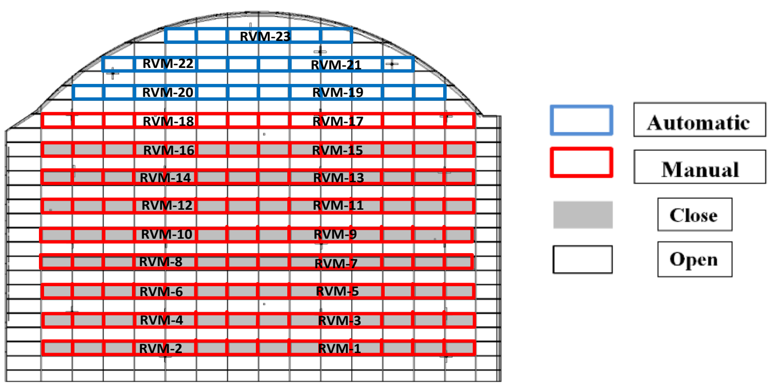


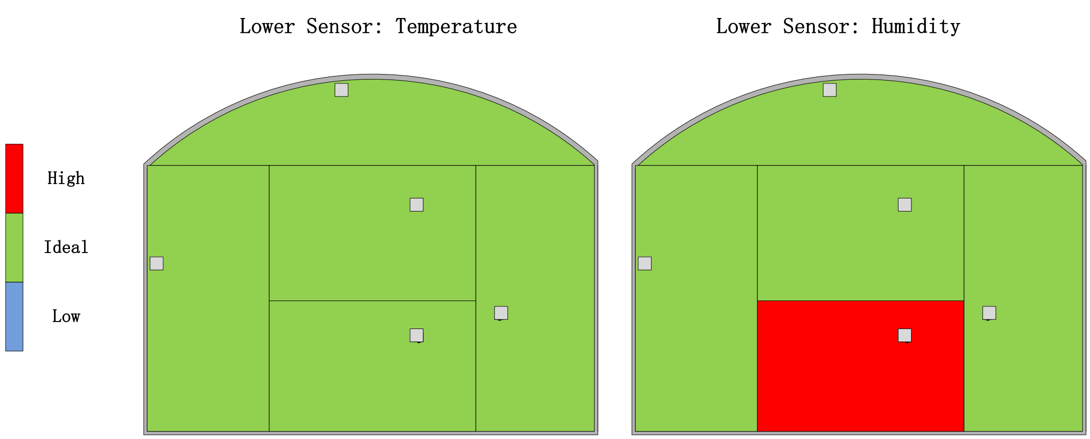
Figure 22. Applicable visualization techniques for the identified information requirements

4.2.2.3 Implementing low-fidelity prototypes

Low-fidelity prototyping was adopted as the method to create prototypes for the various interface design options, which were then used as materials to get operators' feedback. Low-fidelity prototyping has been widely recognized for a long time in HCI domain as an effective technique to demonstrate and test interface design ideas at early stage of projects with real users (Retting 1994). Low-fidelity prototypes have limited real functionalities, but are implemented to depict, communicate, and inform the concepts and design alternatives (Rudd et al. 1996). The other end of low-fidelity prototyping is high-fidelity prototyping, which usually involves developing interfaces almost as functional as the final product's user interfaces (Rudd et al. 1996). Advantages of low-fidelity prototyping method over high-fidelity prototyping method are various, such as lower development cost, quick evaluation of multiple design concepts, and resolution of screen layout issues (Rudd et al. 1996). We chose low-fidelity prototyping because these advantages fit the objective of this research for evaluating multiple design options for BAS interfaces and get rapid feedback from facility operators.

Based on the design options listed in the last section, the low-fidelity prototypes implemented for this research are shown in Figure 23-Figure 28. These prototypes are printed in papers and used as materials in user tests. 2D-based interfaces are shown in Figure 23-Figure 25 and 3D-based interfaces are shown in Figure 26-Figure 28.





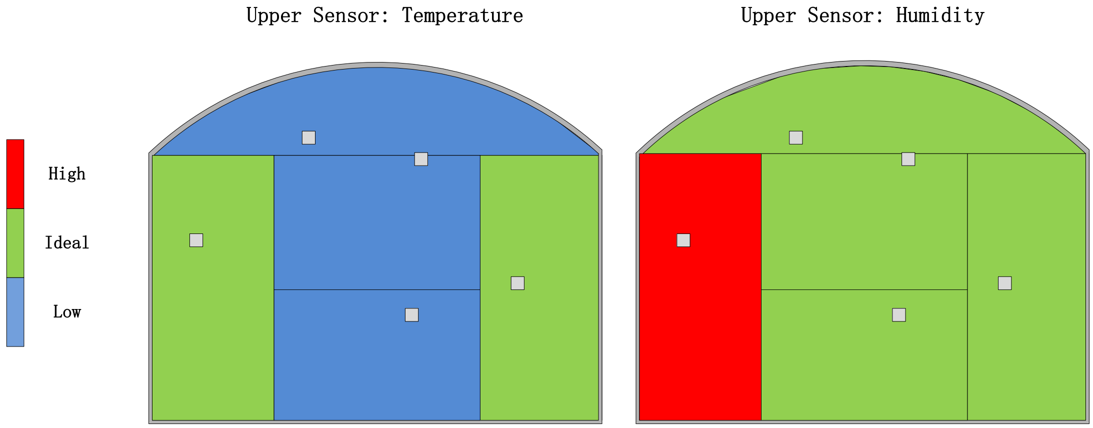


Figure 23. Option 1a: 2D+color coding to show RVM statuses/control modes and sensor readings

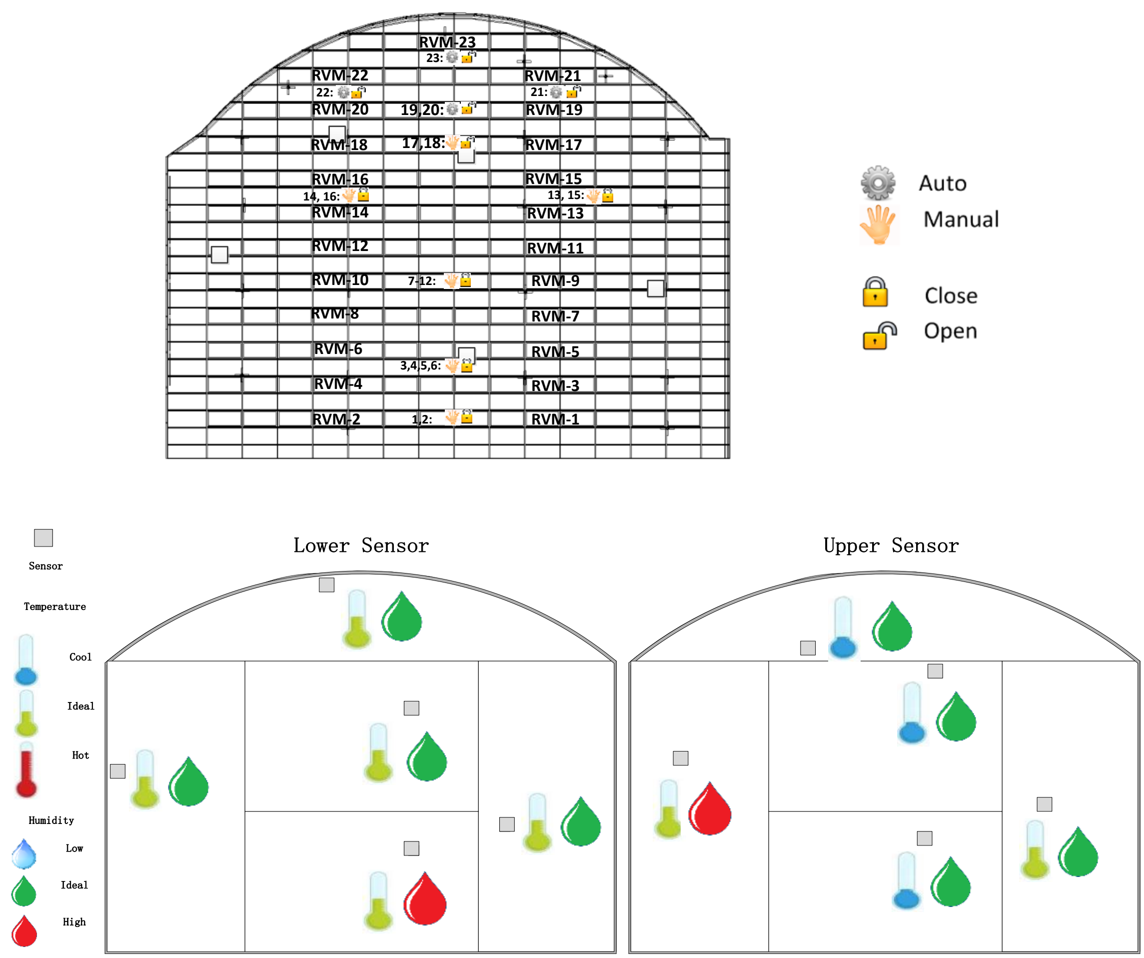


Figure 24. Option 1b: 2D+symbol/metaphor to show RVM statuses/control modes and sensor readings

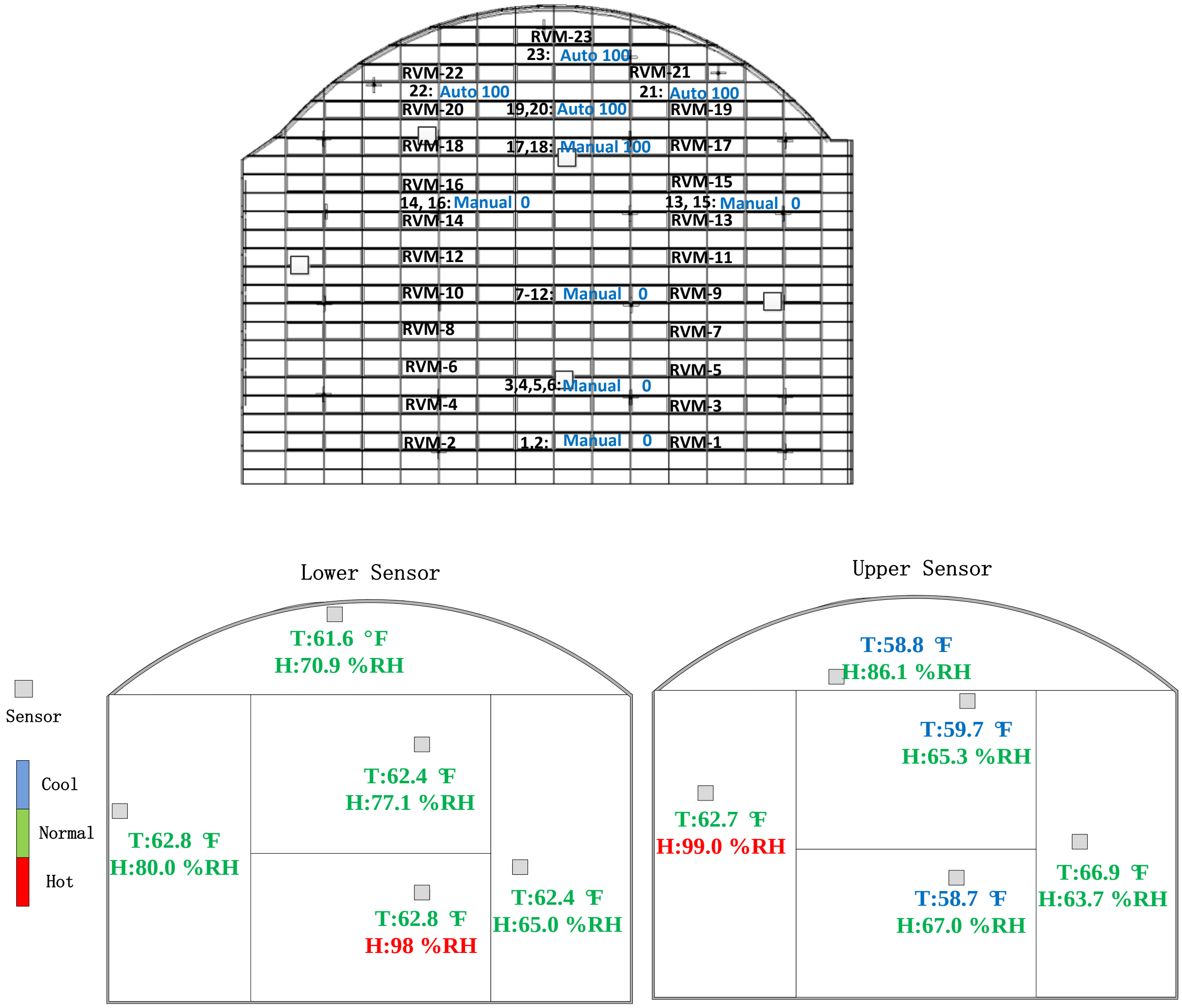


Figure 25. Option 1c: 2D+text annotation to show RVM statuses/control modes and sensor readings

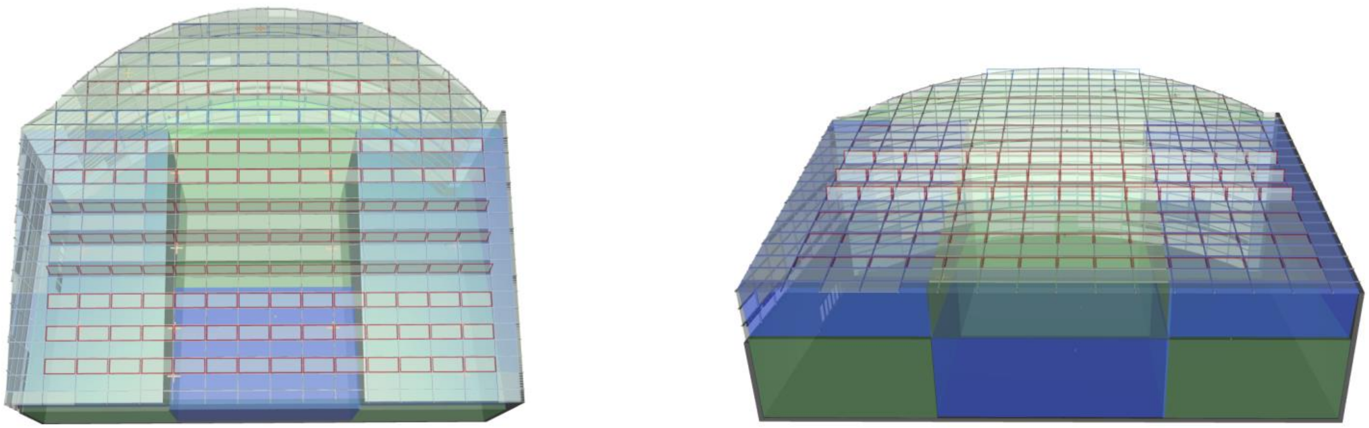


Figure 26.1 Temperature readings are shown in color coded bounding box

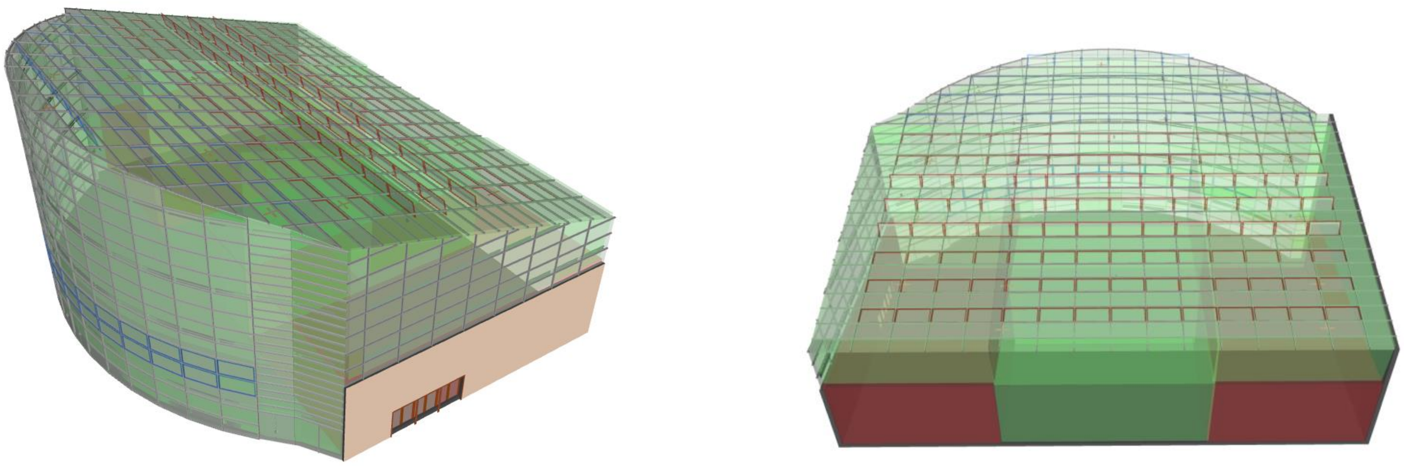


Figure 26.2 Humidity readings are shown in color coded bounding box

Figure 26. Option 2a: 3D+color coding to show RVM statuses/control modes and sensor readings

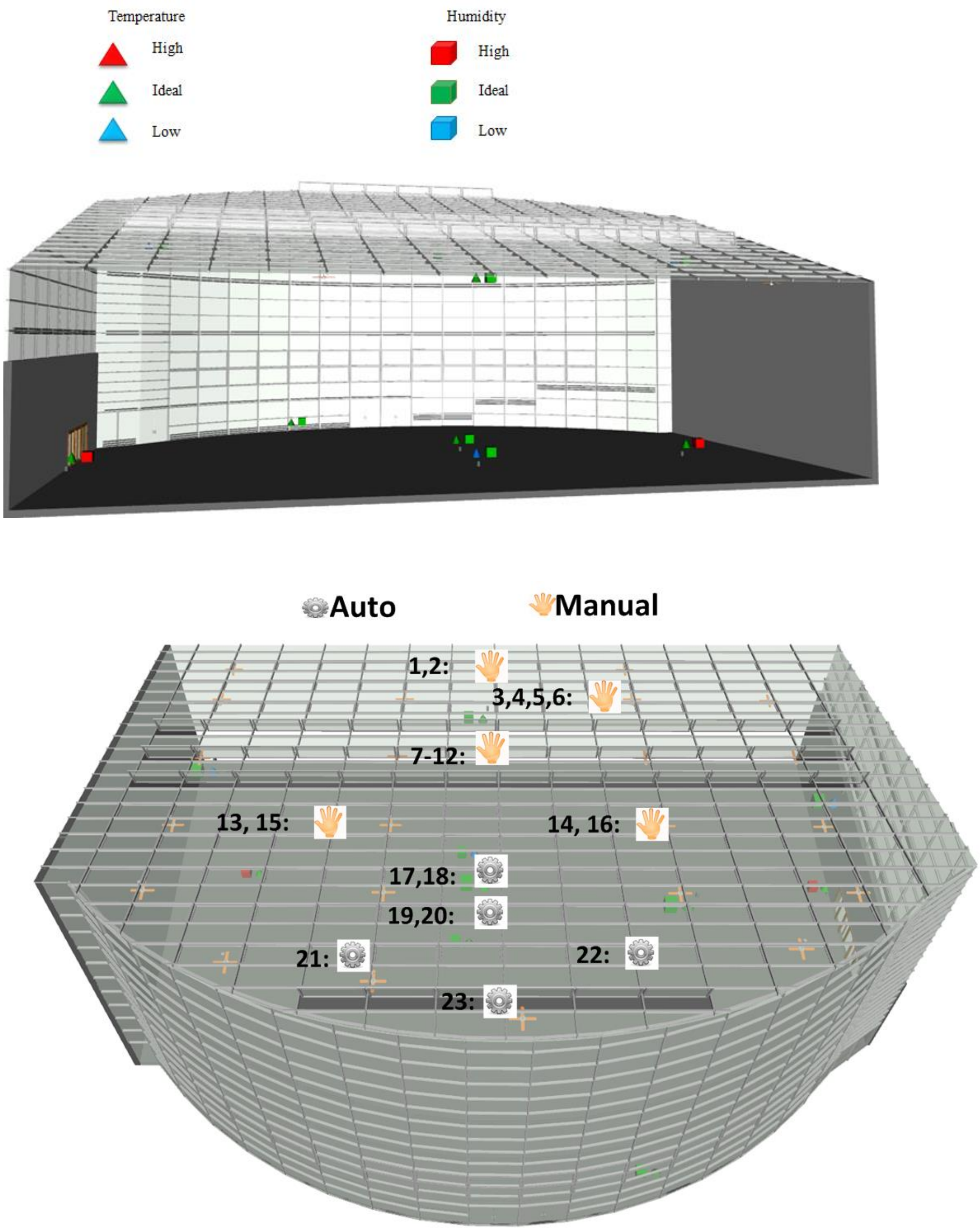


Figure 27. Option 2b: 3D+symbol/metaphor to show RVM statuses/control models and sensor readings

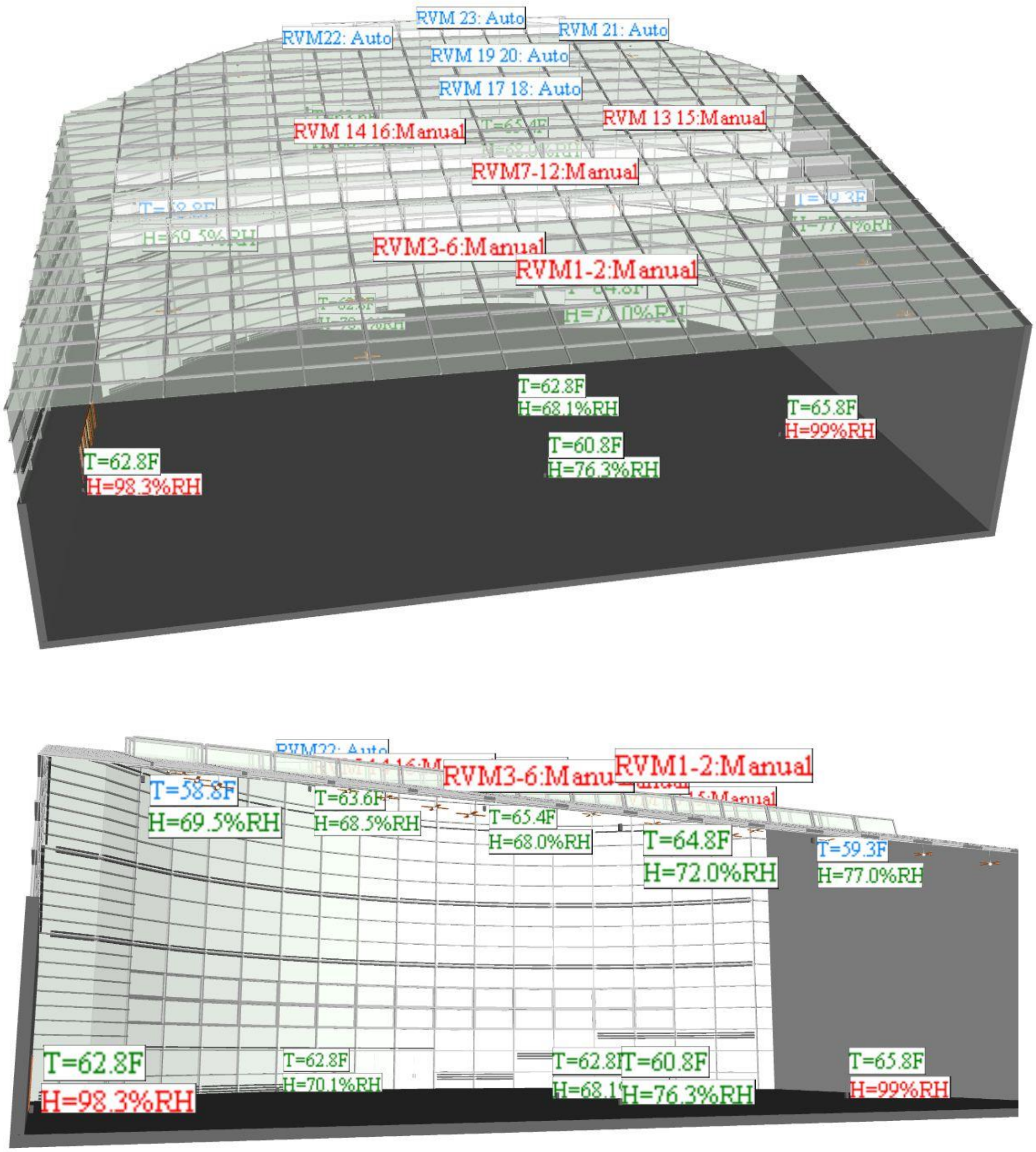


Figure 28.Option 2c: 3D+text overlay/annotation to show RVM statuses/control modes and sensor readings

4.2.3 Design of user tests and participants

The objective of the user tests was to evaluate the various visualization-based interface design options illustrated in the last section. The current interface (Figure 19) and the newly designed visualization-based interfaces (Figure 23-Figure 28) that need to be evaluated were printed on papers as materials for the user tests. Due to the limitation of showing 3D based interfaces on papers, the 3D models were also projected during the user tests and manipulated (e.g., rotate, zoom in/out) based on participants' request. This section describes the participants of the tests and the details of the user tests.

4.2.3.1 Overview of the participants

The participants in the user tests were from three different backgrounds. The participants were divided into three groups based on their domain knowledge on facility operations in general, and their familiarity with the specific greenhouse facility used in the user tests, as shown in Table 16. The reason why we differentiated the group backgrounds was to observe the effects of domain expertise and familiarity with the specific space layout on the research findings.

Table 16. Profiles of participating groups in the user tests

	Participants	**Experience level with facility operations in general**	**Familiarity with operation of the greenhouse facility**
Group 1	4 greenhouse facility operators	Expert	Expert
Group 2	13 building operators	Expert	Novice
Group 3	6 graduate students	Novice	Novice

The first set of participants (i.e., Group 1) included four facility operators from the greenhouse facility which we used as the testbed for the user tests. They are experienced employees in the greenhouse facility and very familiar with the current BAS interface and the space layouts. The second group (i.e., Group 2) was formed with participants from another facilities management services group that was responsible for the operation of buildings in a campus. There were thirteen experienced building operators in Group 2, who deal with 8 different types of BASs in the campus buildings in their daily work. The participants in this group were domain experts in facility operations using BASs, but were considered as novices for space familiarity for the specific greenhouse facility used in the tests, as they were not familiar with the space and the BAS in use. The last group incorporated six graduate students majoring in Civil and Environmental Engineering and only had basic understanding of building operations. They were novices in terms of facility operations and space familiarity.

4.2.3.2 Evaluation metrics

Both quantitative and qualitative metrics were used to evaluate the performance of the operators while using the 3 sets of interfaces for facility monitoring. Quantitative metrics included (1) *Accuracy* of completed tasks in terms of whether participants completed them correctly or not; (2) *Efficiency* of participants in terms of how long it took them to complete the tasks within given scenario settings. Qualitative metrics such as participants' subjective *preferences* are also important because it is possible that quantitative measurements are not sensitive enough to detect differences in used visualization techniques and users may be spending different level of mental efforts to interpret the visual forms [63]. Mental efforts, i.e., cognitive load, can be measured by sending participants post-test questionnaires to ask their preferences of different interface design options [64]. In this research, the participants' ratings for each option were used as a qualitative metric.

4.2.3.3 Procedure for user tests

At the beginning of a session, I gave the participants a short introduction on the functionality of the greenhouse facility, the types of equipment being controlled, the sensor information and the BAS control logic since majority of the participants were not familiar with the facility and its instrumentation. I also explained the tasks that the participants would need to do during the tests.

The tasks are a typical monitoring tasks that the greenhouse facility operators need to do daily as described in section 4.1, which were described as: "please identify the sensors that could be faulty" given that (a) the outside temperature is 45 °F and (b) the specified zone has just been watered, and (c) the current sensor readings and RVM statuses/control modes are shown in the interfaces. It was expected that the participants would understand that the upper level sensors would typically have higher temperature readings as compared to lower level sensors because of the rise of warm air. However, when the roof vents are open, upper level sensors that are directly under these open vents would have temperature readings that are lower than their typical readings. Similarly, the participants were expected to get an understanding that the lower level sensors would have significantly high humidity readings when nearby trees were watered. Based on this information and logic, the participants also received a short training where all the designed interface options were used to complete these two tasks in a sample scenario setting, where different set of sensor readings and different rows of RVM with different statuses were used, as compared to the scenario settings used in the real tests.

In the user tests, the participants completed the given tasks three times, each time under a different scenario setting and using a set of interfaces (i.e., the current interface, 2D-based interfaces and 3D-based interfaces). The main reason to give the same tasks in different scenario settings was to eliminate the possibility that a user would remember the correct answer they got in a previous round where they used a specific set of interfaces. Each scenario setting was different in terms of the sensor readings, the rows of roof vents being open and zone being watered, and was used to evaluate a given interface set, as shown in Table 17. Furthermore, in order to eliminate the possibility that the participants would get familiar with the tasks and would perform better in the tasks while using subsequent interfaces, I further divided each group of participants into three sub-groups, and each sub-group received the three sets of interfaces in a different order. Table 17 shows the scenario settings used for different sets of interfaces and the order in which each group received the designed interfaces.

Table 17. Scenario settings used in the tests and the order in which each group received the material

		Current interface	**2D-based interfaces**	**3D-based interfaces**
Scenario settings (sensor readings/statuses are shown in Figure 23 to Figure 28)		Zone 1 was watered; Only the roof vents 14-16 and 23 were open	Zone 3A was watered; Only the roof vents 17-23 were open	Zone 2 was watered; Only the roof vents 7-12 and 23 were open
Group 1: 4 greenhouse facility operators				
Group 1.1	2 greenhouse facility operators	1*	2	3
Group 1.2	1 greenhouse facility operator	3	1	2
Group 1.3	1 greenhouse facility operator	2	3	1
Group 2: 13 campus building operators				
Group 2.1	5 Campus building operators	1	2	3
Group 2.2	4 Campus building operators	3	1	2
Group 2.3	4 Campus building operators	2	3	1
Group 3: 6 graduate students				
Group 3.1	2 graduate students	1	2	3
Group 3.2	2 graduate students	3	1	2
Group 3.3	2 graduate students	2	3	1

*Note: number means the order in which the corresponding interface was received by a participating subgroup

When using 2D or 3D based interfaces, since there were multiple options to encode the semantic information in spatial settings, the participants were asked to evaluate these options in a 1-5 Likert scale and define their preference through post-test questionnaires.

4.2.4. Research Findings

This section summarizes the findings from the user tests, and analyzes the results from the three evaluation metrics: accuracy, efficiency and users' preferences for the three different groups of participants.

(1) Accuracy of decisions in relation to the assigned tasks

The first metric to evaluate the performance of different interfaces was the accuracy rate for participants to complete the tasks. The accuracy of the participants' responses while they used three sets of interfaces was recorded in terms of 0% accuracy, 50% and 100% accuracy. There were two tasks in each session of the user test, namely finding the upper level sensor that shows an abnormally low temperature reading and the lower level sensor that shows an abnormally high humidity reading. If the participant correctly identified the sensors in both tasks, the accuracy rate was recorded as 100%, if the participant identified only one of the sensors correctly, the accuracy rate was 50%, and if the participant could not identify the correct sensors in both tasks, the accuracy rate was recorded as 0%. The average accuracy rate of each group's decisions for the evaluated interfaces is provided in Table 18.

Table 18. Average accuracy rate of decisions for the tasks

	Current interface	**2D-based interfaces**	**3D-based interfaces**
Group 1: 4 greenhouse facility operators	100%	100%	100%
Group 2: 13 campus building operators	71%	93%	63%
Group 3: 6 graduate students	83%	92%	75%

The four facility operators from the greenhouse facility achieved 100% of accuracy rate for all interfaces, which can be explained by their familiarity with the facility and the assigned tasks. For building operators and graduate students, accuracy in the tasks increased (i.e., 22% for building operators and 9% for graduate students) when the participants used the 2D-based interfaces as compared to the current interface. However, the average accuracy rate of decisions of both building operators and graduate students tended to drop (i.e., 8% for both building operators and graduate students) as compared to the current and 2D-based interfaces when they used 3D-based interfaces. Follow-up interviews with the participants revealed the fact that the most important drawback of 3D-based interfaces was the static viewpoint of the environment within the 3D interfaces, which resulted in having a partial understanding of the facility operation status at a given point in time. In order to have an overall understanding of the entire facility, they needed to look from different viewpoints, which made them feel disoriented and confused about understanding which part of the facility they were looking at. This problem was not observed for the two greenhouse facility operators because they were already very familiar with the facility and comfortable with looking from different viewpoints without feeling disoriented.

(2) Efficiency of participants in completing user tests

The second metric to evaluate the performance of different interfaces is the efficiency, which is the time recorded in the user tests. The time for the participants to complete the tasks is analyzed statistically as shown in Figure 29-Figure 31.

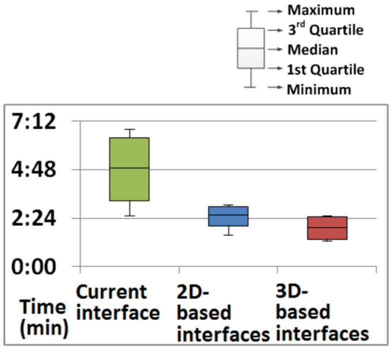


Figure 29. Completion time for the greenhouse facility operators

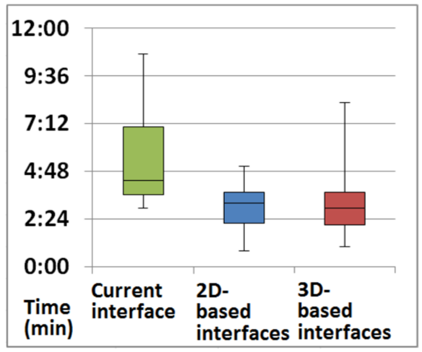


Figure 30. Completion time for the building operators

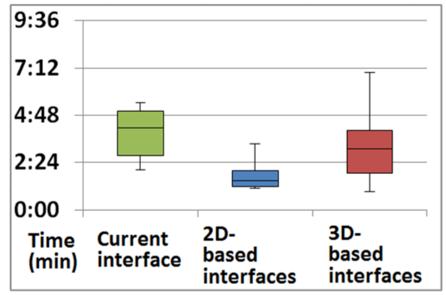


Figure 31. Completion time for the graduate students

When Figure 29 is analyzed, it is found that there is a reduction in time by 48% and 60% (in median) to complete the tasks for the four greenhouse facility operators using the 2D-based and 3D-based interfaces, compared with the current interface. In addition, statistical test (t-test) indicates that there is significant ($p<0.05$) time decrease for both 2D-based interfaces and 3D based interfaces, when comparing with current interface. But there is no significant ($p>0.05$) difference between 2D-based interfaces and 3D-based interfaces, which suggests that the greenhouse facility operators perform equally well when using the two sets of visualization-based interfaces.

For the building operators from other institutions, it is observed from Figure 30 that there is a similar time reduction trend, with 26% and 32% decrease (in median) when they were using 2D-based interfaces and 3D-interfaces to complete the tasks, compared with the time devoted by the operators while using the current interface. Both 2D and 3D-based interfaces enabled significant efficiency improvement ($p<0.05$) as compared to efficiencies of operators when they used current interfaces, but there is no significant difference between the two sets of visualization-based interfaces. Building operators performed well when using the two sets of visualization-based interfaces. Thus, the results indicate that the efficiency of the facility operators that are expert in facility operations but not familiar with the spatial context of the facility being monitored increase when 2D and 3D based visualization techniques are used in the BAS interface.

Furthermore, Figure 31 indicates that utilization of 2D-based interfaces for facility monitoring is generally the most efficient one for Group 3 and this set of interfaces resulted in 65% time reduction as compared to current tabular interfaces, and the statistical analysis suggests the time reduction is significant ($p<0.05$). Although 26% drop in median time was observed in operator efficiencies when they used 3D-based interfaces as compared to cases where they used current interfaces, there is no significant difference ($p>0.05$) between the two. Thus, it implies that graduate students performed best when they used 2D-based interfaces for facility monitoring. This evidence suggests that 2D-based interfaces are better for novices who are neither familiar with the spatial context under which the BAS operates, nor with the facility operations.

The research findings presented in this chapter section on the improvement of accuracy and efficiency for monitoring tasks of facility operations using visualization-based interfaces are different from the findings identified by Hsieh and Lu (2012), in terms how 3D-based interfaces affect operators' performance. Hsieh and Lu (2012) have identified that there is a consistent improvement of efficiency for the monitoring of field settlements while maintaining the same accuracy level using 3D-based interfaces. In contrast, the findings in this study suggest that whether 3D-based interfaces can help achieve better operator-performance depends on the familiarity of the facility operators with the spatial layout of the facility they monitor. If the facility operators are not familiar with the spatial layout of a facility, they tend to get disoriented and feel lost in the space when they need to look at the 3D facility from different viewpoints and their performance decreases. In such a setting, the findings show that the operators perform better in understanding the situation when 2D-based interfaces are used.

(3) Users' preferences on using different interfaces

This metric was to give a qualitative evaluation in terms of users' personal preferences on different sets of interfaces. Figure 32-Figure 34 show the average rating for each design option graded by the greenhouse facility operators, building operators and graduate students.

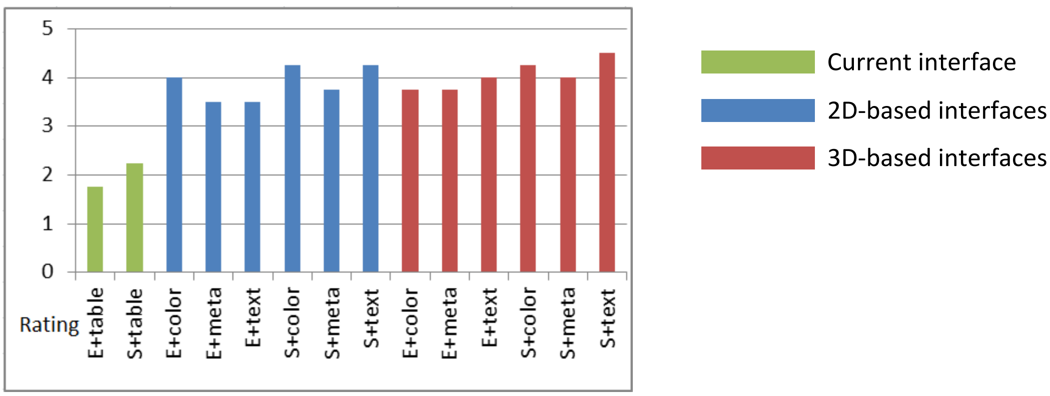


Figure 32. Greenhouse facility operators' average rating for each design option

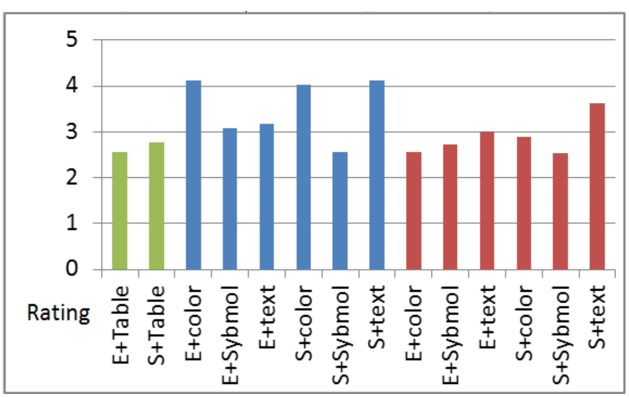


Figure 33. Building operators' average rating for each design option

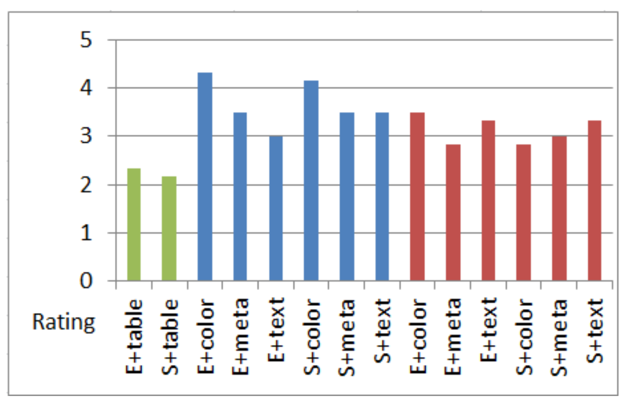


Figure 34. Graduate students' average rating for each design option

Note: E+table: use tabular format to show equipment statuses; S+table: use tabular format to show sensor readings; E+color: use color coding to show equipment statuses; E+meta: use metaphor to show equipment statuses; E+text: use text annotation to show equipment statuses; S+color: use color coding to show sensor readings; S+meta: use metaphor to show sensor readings; S+text: use text annotation to show sensor readings

It is suggested from the ratings that all groups of participants generally like visualization-based interfaces better than current tabular interface, because none of the 2D-based interfaces or 3D-based interfaces received lower ratings than current tabular interface. Greenhouse facility operators, who were familiar with the spaces, identified 3D with text overlay as the most preferred option to interpret sensor readings and equipment statuses. Given this, when facility operators are experienced in their work and have familiarity about the spatial setting, 3D-based interfaces should be preferred. Building operators who are expert in operations but are not familiar with the spaces being monitored struggle to put the sensor readings in spatial context and prefer 2D with text overlay as the preferred interface to work with. Novices also prefer to look at the sensor readings and equipment statuses in 2D settings with color coding, due to lack of self-orientation in 3D views.

4.3 Evaluation of integrated visualization platform for troubleshooting of HVAC related problems

The objective of the study presented in this chapter is to develop a visualization platform to provide the required information for HVAC mechanics and evaluate the platform in terms of how much efficiency it would bring to diagnosing of causes for HVAC related problems. The development process followed a user-centered, iterative design process, and the final product is evaluated through user studies with quantitative metrics. The research method includes five steps: (1) identifying what information to visualize and applicable visualization techniques, (2) implementing low-fidelity prototypes for the visualization alternatives, (3) getting users' feedback about the alternatives, (4) implementing high-fidelity prototype based on users' feedback; (5) evaluating the high-fidelity prototype by user studies, and will be detailed below:

4.3.1 Identifying what information to visualize and applicable visualization techniques

The first step of the research was to understand what information HVAC mechanics need when they work on troubleshooting of HVAC related problems. I conducted various studies (including shadowing, interviews, and focus groups, together with extensive literature review and investigation of systems they use) to define the information HVAC mechanics typically use. The results of the research have been presented in details in Yang and Ergan (2014a). These information requirements need to be analyzed to determine if they need to be visualized and if so, what visualization techniques are applicable.

As explained in the background research, the information that needs to be visualized should be either spatial, high-dimensional or should have semantic information that is associated with the spatial or geometrical properties of objects. Since there is no high-dimensional data involved in the required information for troubleshooting, the information visualization techniques using different charts or diagrams are not applicable in this context. In addition, too many information items visualized at the same time will make the view messy or cluttered, which will aggravate information overloading problem (Strother et al. 2012). This study focuses on the visualization of a subset of the identified information requirements, which have medium to high referral rates. Therefore, the required information that (a) is associated with tangible objects, where the spatial or geometrical information of objects are to be displayed, (b) has medium to high referral rates by HVAC mechanics will be used in the visualization study. The set of information that comply with these constraints includes (a) HVAC component static information - location and control relationships, (b) HVAC component dynamic information – the readings/setpoints of controlled parameters and control commands, and (c) HVAC component historical information - previous problem types, maintenance date, remedy actions, and responsible person. Based on the visualization techniques classified in Table 14 and the data types of the information items (being categorical, scalar, etc.), the applicable visualization techniques are provided in Table 19.

Table 19. Applicable visualization techniques to the medium/highly referred information items

Information	**Data types**		**Applies to multiple HVAC components?**	**Spatial information visualization techniques**	**Semantic information visualization techniques**
HVAC component static information	Location	Spatial	Yes	2D floor plan and 3D model	N/A
	Control relationships	Topological	Yes	Block diagram; Schematic diagram	N/A
HVAC component dynamic information	Setpoints of controlled parameters	Scalar	Different per component	Schematic diagram and 3D model	Text overlay/annotation
	Readings of measured	Scalar	Temperature readings		Text overlay/anno

	parameters		apply to multiple components		tation; Color coding; Symbol/metaphor
	Control commands	Scalar	Different per component		Text overlay/annotation
HVAC component historical information	Previous problem types	Categorical	Yes	Schematic diagram and 3D model	Text overlay/annotation; Color coding; Symbol/metaphor
	Remedial actions	Categorical	Yes		
	Date/time stamp	Scalar	Yes		
	Responsible personnel	Categorical	Yes		

4.3.2 Implementing low-fidelity prototypes

Low-fidelity prototyping (Retting 1994), which is used to create imitated interfaces rapidly without actually implementing the functionalities of an end product, has been widely adopted in HCI domain to develop user interfaces. Low-fidelity prototypes are usually graphical paper-based prototypes to demonstrate the possible design options. They are fast to create at low cost at the early stages of user interface design process and are effective to get users' feedbacks before many efforts are devoted in developing the real products. In this study, various visualization options for the information that should be visualized were implemented using the low-fidelity prototyping method and feedbacks on the different design options were gathered through user studies with thirteen HVAC mechanics from different FM groups with experience levels ranging between 5 and 38 years.

The developed low-fidelity prototypes are based on the applicable visualization techniques as shown in Table 19. When combining the options for spatial contexts and the options for encoding semantic information in spatial contexts, the possible visualization options are shown in Figure 35:

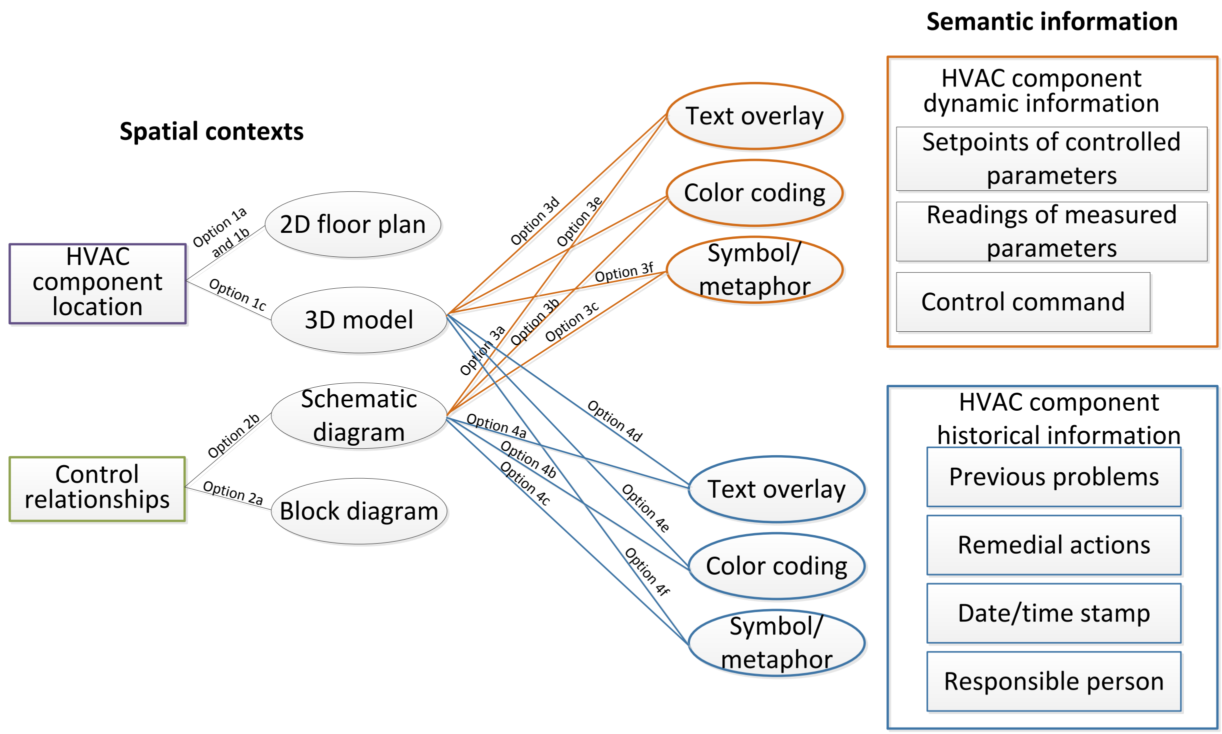
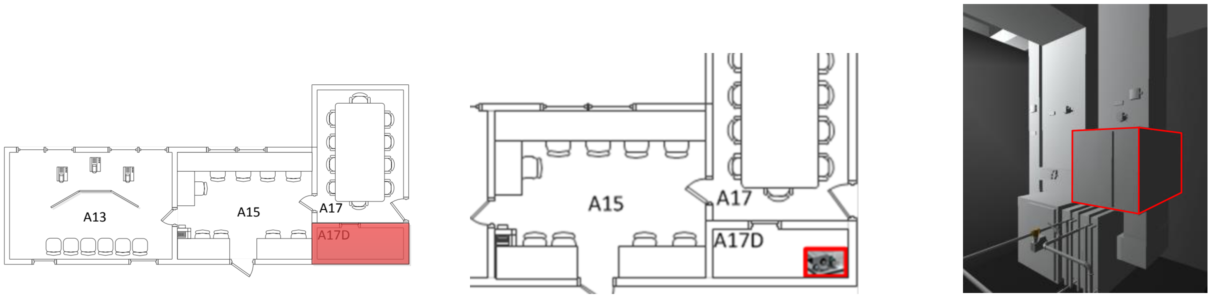


Figure 35. Applicable visualization techniques for the required information of HVAC troubleshooting tasks

The detailed descriptions about these visualization options are provided below:

(1) Visualization options for component location information

An HVAC component's location represents a spatial information item, which can be visualized in a 2D floor plan or in a 3D model. It was identified that the location information means different data to different HVAC mechanics, such as the room ID where the component is located, bounding box of the component in that room in 2D, or the bounding box of the component in the 3D space. The possible visualization options implemented by low-fidelity prototypes are shown in Figure 36 for HVAC component location information. The figure shows an AHU fan.

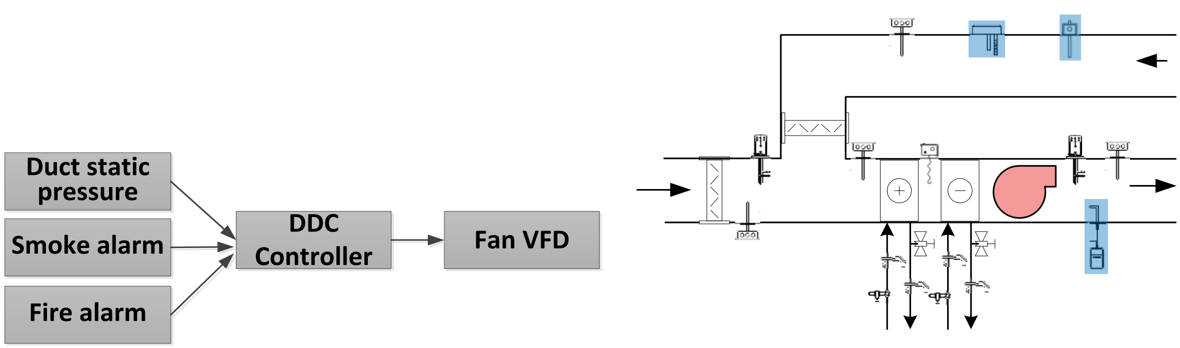


Option 1a Option 1b Option 1c

Figure 36. Visualization options for component location information

(2) Visualization options for control relationships between HVAC components

The control relationships between HVAC components constitute topological information. Examples of control relationships include thermostat controls a zone damper, and a fan is controlled by static pressure sensor. As detailed in the background section, two common ways to display control loops are block diagrams and highlighted components in schematic diagrams, as shown in Figure 37 option 2a and 2b, respectively. The figure shows an example of the control relationships for a fan of an AHU with three sensors.



Option 2a Option 2b

Figure 37. Visualization options for control relationships information of HVAC components (sensors are highlighted with blue and the fan is highlighted in red in option 2b)

(3) Visualization options for HVAC component dynamic information

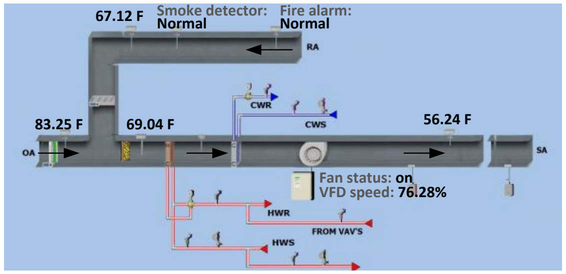
Schematic diagrams represent a common way to visualize the configurations of HVAC systems in details, whereas block diagrams show the interrelationships between the main control functions. Schematic diagrams, due to their nature, constitute a 2D way of showing spatial context for HVAC components. 2D floor plans and block diagrams are not applicable in this case as they cannot give a bird eye view for spatial context of HVAC systems. 3D model is another option to visualize the spatial context of HVAC systems.

The current visualization techniques that have been adopted by commercial BAS vendors to show dynamic information of HVAC components include using text annotations on schematic diagrams of HVAC systems as shown in Figure 38 option 3a. However, the text overlay/annotation on schematic diagram is only one of the possible options to visualize HVAC component dynamic information according to Figure 35. HVAC component dynamic information includes the setpoints of controlled parameter, the readings of measured parameters and control commands, which represent scalar data. The data types for HVAC component dynamic information are different for different types of components. For example, the setpoints and current readings for a temperature sensor is in °F, whereas the setpoints and current readings for a pressure sensor is in psi or inch of water; the control command for a fan is the percentage of speed, whereas the control command for a damper or a valve is the percentage of opening. As explained in the background research of the section 2.3, to effectively use color/pattern coding and symbol/metaphor visualization techniques, the information that needs to be visualized should be applicable to multiple objects. Therefore, the only applicable visualization technique for general dynamic information is text overlay/annotation. However, a subset of parameter readings of measured parameters – air temperature readings, are measured by various sensors in different sections of ductwork, such as outside air temperature reading, return air temperature reading, mixed air temperature reading, and discharge air temperature, which can be visualized using color/pattern coding and symbol/metaphor visualization techniques. The combinations of visualization techniques for spatial contexts, and for encoding semantic information in spatial contexts create the applicable options for HVAC component dynamic information, as shown in Figure 35 options 3a-3f, and the implemented low-fidelity prototypes are shown in Figure 38.

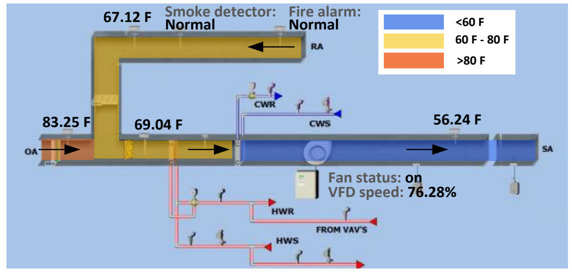
(4) Visualization options for HVAC component historical information

HVAC component historical information that is frequently required by HVAC mechanics includes previous type of problems (i.e., temperature, air flow, humidity, odor, water leak, and noise), the date/time stamp, the remedial actions taken [i.e., adjust, replace, repair, and preventive maintenance (PM)], and the name of the responsible personnel. The information items are either categorical data or scalar data, and they are applicable to all HVAC components, which can be visualized by color coding, symbol/metaphor, and text overlay/annotation. Similarly, combined with two options to visualize HVAC system spatial contexts, there are six options to visualize HVAC component historical information, as shown in Figure 35 option 4a-4f. The implemented low-fidelity prototypes are shown in

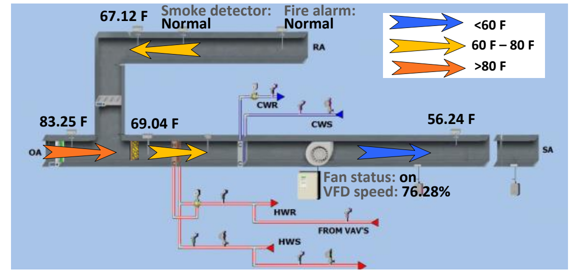
Figure 39. The figure shows an example of visualizing remedial actions for HVAC components.



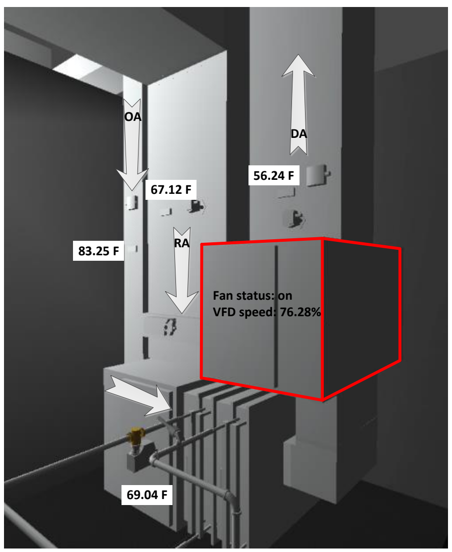
Option 3a



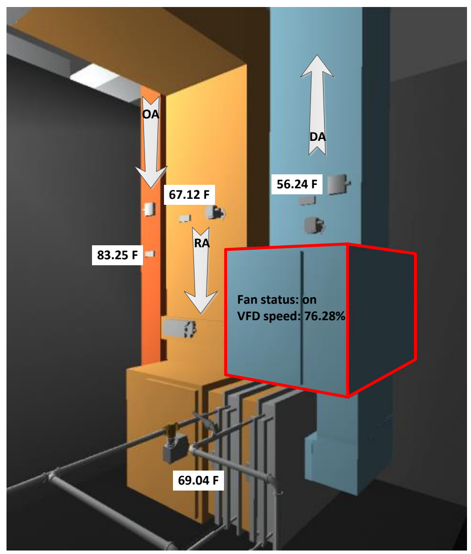
Option 3b



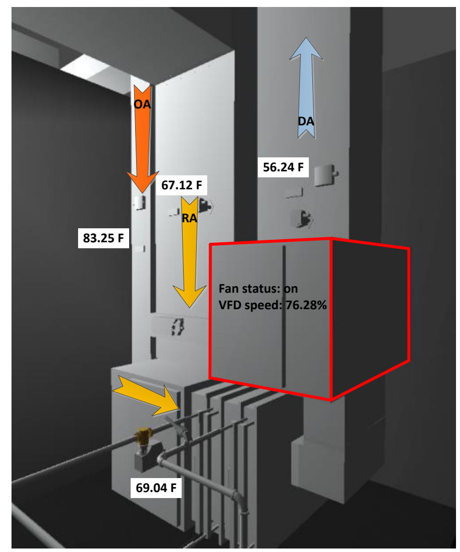
Option 3c



Option 3d

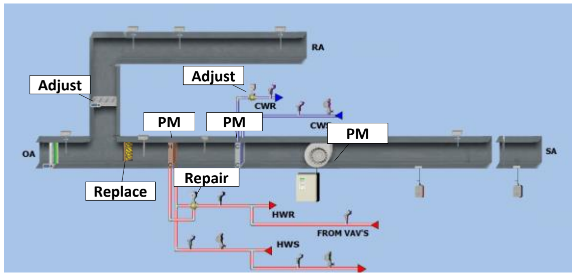


Option 3e

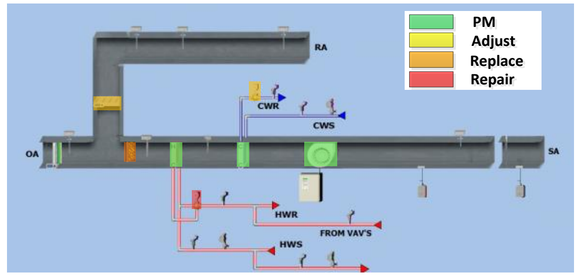


Option 3f

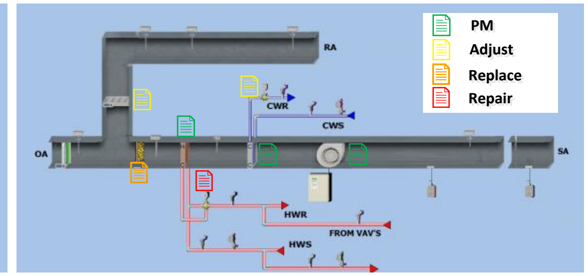
Figure 38. Visualization options for component dynamic information



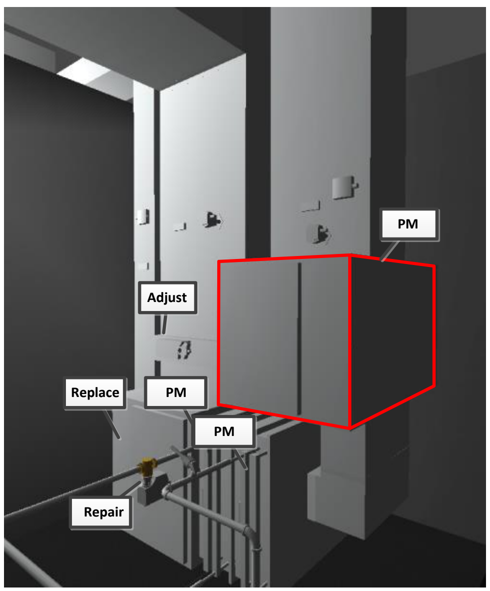
Option 4a



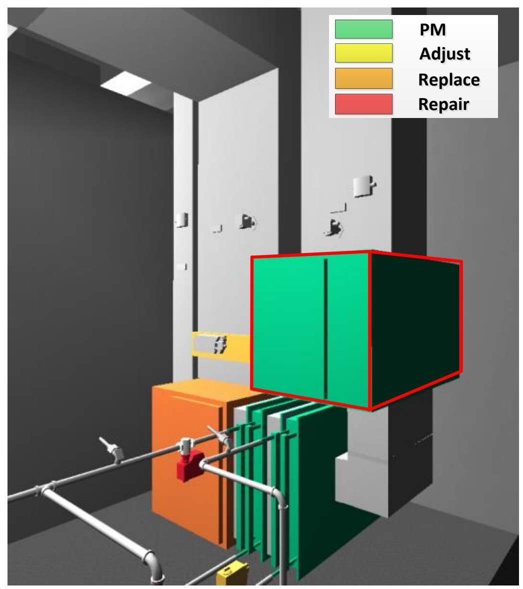
Option 4b



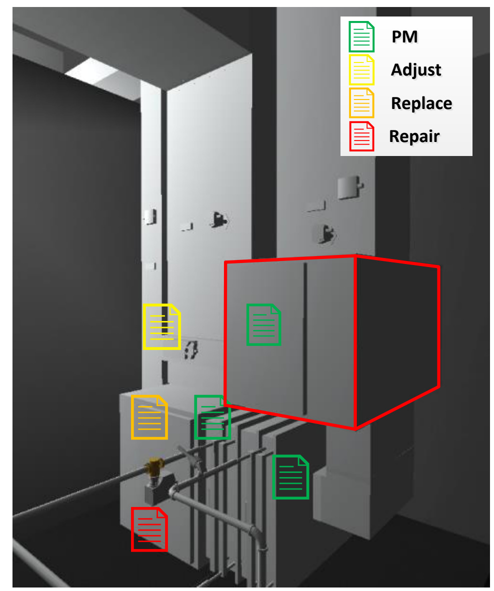
Option 4c



Option 4d



Option 4e



Option 4f

Figure 39. Visualization options for HVAC component historical information

4.3.3 User studies with low-fidelity prototypes

There were a total of thirteen HVAC mechanics from two different FM groups, who participated in the low-fidelity prototyping user studies. They have an average of 21 years' experience working at HVAC maintenance domain. The user studies at this phase include face to face user studies. I first explained the different visualization options and then the participants were asked to give a score for each of the visualization options selecting from a Likert scale from 1-5, which is respectively as: **Strongly Dislike, Dislike, Neutral, Like**, and **Strongly Like,** and pick the options that they like the best for each information category in order to be able to eliminate the options that were disliked or never picked as the best option. The participants could ask questions when they got confused about certain visualization options and they were encouraged to give comments about whether they like/dislike certain option, and suggestions about other possible visualization options. Two metrics were used as the guideline to decide which options need to be implemented in high-fidelity prototyping: (a) the average score for each visualization option; and (b) the number of participants who picked each the visualization option as their favorite.

The results of the user preferences for the visualization options given in low-fidelity prototypes are shown in Figure 40 - Figure 43. In Figure 40.1- Figure 43.1, the x-axis is the visualization options and the y-axis is the average score. Figure 40.2 - Figure 43.2 show the number of participants who picked different visualization options as their favorite.

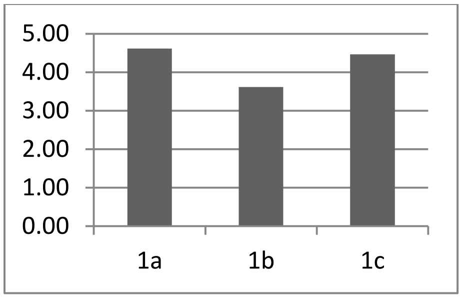


Figure 40.1. Average score for options to visualize *location* information

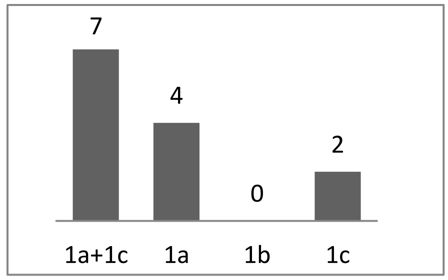


Figure 40.2. Number of participants who picked different options as favorite to visualize *location* information

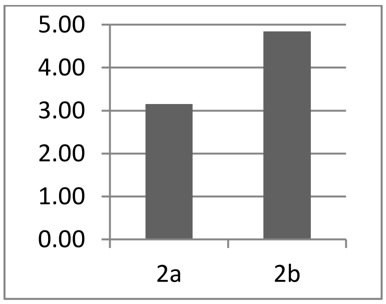


Figure 41.1. Average score for options to visualize *control relationship* information

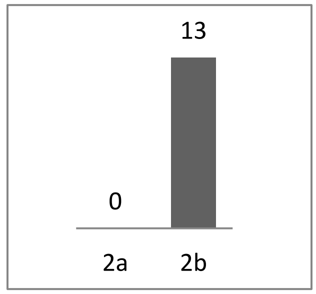


Figure 41.2 Number of participants who picked different options as favorite to visualize *control relationship* information

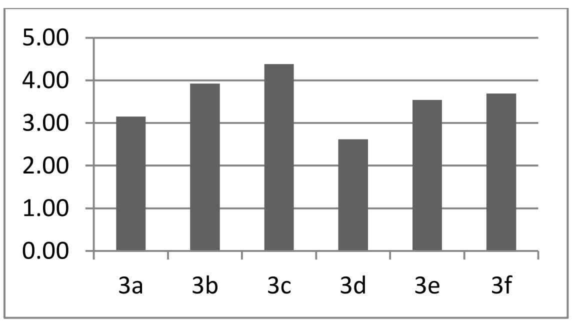


Figure 42.1. Average score for options to visualize *dynamic* information

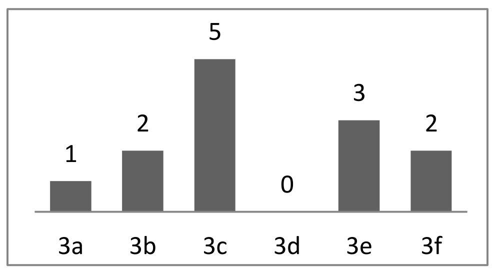


Figure 42.2. Number of participants who picked different options as favorite to visualize *dynamic* information

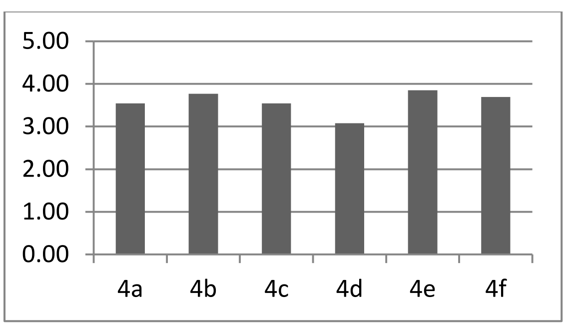


Figure 43.1 Average score for options to visualize *historical* information

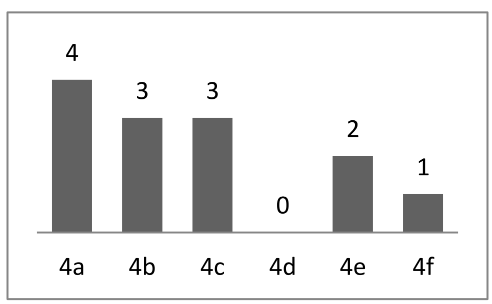


Figure 43.2. Number of participants who picked different options as favorite to visualize *historical* information

For HVAC component location information, the option of marking space ID on floor plan (option 1a) and highlighting in 3D view (option 1c) received higher average scores (4.62 and 4.46) than marking the 2D location information on floor plans (option 1b) (3.62). Because these three options give different levels of details about the location information, the participated HVAC mechanics were also allowed to pick multiple options if they would prefer. When asked about what option they like the best, most of the participants (7/13 HVAC mechanics) indicated that they would like to see the space ID on floor plan (option 1a) first and then go to the detail of 3D location in the space (option 1c). This conforms to the concept of "focus plus context" in the HCI domain, which means that users need to see the object of interest displayed in detail (focus) while getting an overview (context) about the surrounding information simultaneously (Card et al. 1999). In this case, the floor plan marked with the space where the component locates is the context, and the 3D view of the component is the focus with details. In addition, four HVAC mechanics preferred marking the space ID on the floor plans (option 1a), and two HVAC mechanics preferred the 3D models as their best options (option 1c). Therefore, I concluded that both option 1a and option 1c should be available to users to display the location information for an HVAC component, because this will satisfy all participants' preferences. For the control logic information of HVAC components, highlighting the related components in a schematic representation of the HVAC system (option 2b) received much higher score (4.85) than a block diagram (option 2a) (3.15) and all the participants indicated that they liked option 2b better than option 2a. Hence I concluded that option 2b should be available to users to display the control logic information for HVAC components.

For HVAC component dynamic information, as can be seen from Figure 42, the options that use schematic diagrams (3a, 3b, 3c) to visualize spatial information generally received higher scores than those options that used 3D models to show spatial information, which can be explained by the fact that using schematic diagram to show dynamic data is the common practice used by commercial BAS vendors and thus HVAC mechanics are used to this type of visualization interfaces. For the given six options, except using text overlay/annotations on 3D models (option 3d), all options received an average score below 3 (2.62; 3 stands for **Neutral)**, the technique of using symbol/metaphor on schematic diagrams (option 3c) received an average score above 4 (4.38; 4 stands for **Like**), and all the rest of the scores were close to 3 and 4. In addition, all options had at least one HVAC mechanic that indicated the option as their favorite, except option 3d. Therefore, no single option could be determined as the best option in this category of information and a flexible visualization interface which enables the users to configure the visualization option based on their personal preferences was implemented for high fidelity user studies.

Regarding the HVAC component historical information, the differences between various options are less significant (Figure 43.1). All visualization options received a score between 3 (**Neutral**) and 4 (**Like**), and no obvious preferences were found from the participated HVAC mechanics. All options were selected by at least one HVAC mechanic as the best, except option 4d (Figure 43.2). Therefore, for HVAC component historical information, I also decide to implement a flexible visualization interface. The visualization requirements for different information item identified from low-fidelity prototyping user studies are summarized in Table 20.

A note here is that the preference findings were based on 13 participated HVAC mechanics, and the average scores and favorite options may change with participants' background, training and the existing computerized tools they use. For example, if the participated HVAC mechanics from a different FM group are already very familiar with software using 3D facility model for their daily job, the design options of using 3D view may receive higher scores and have more participates selected as favorite.

Table 20. Visualization requirements identified from low-fidelity prototyping user studies

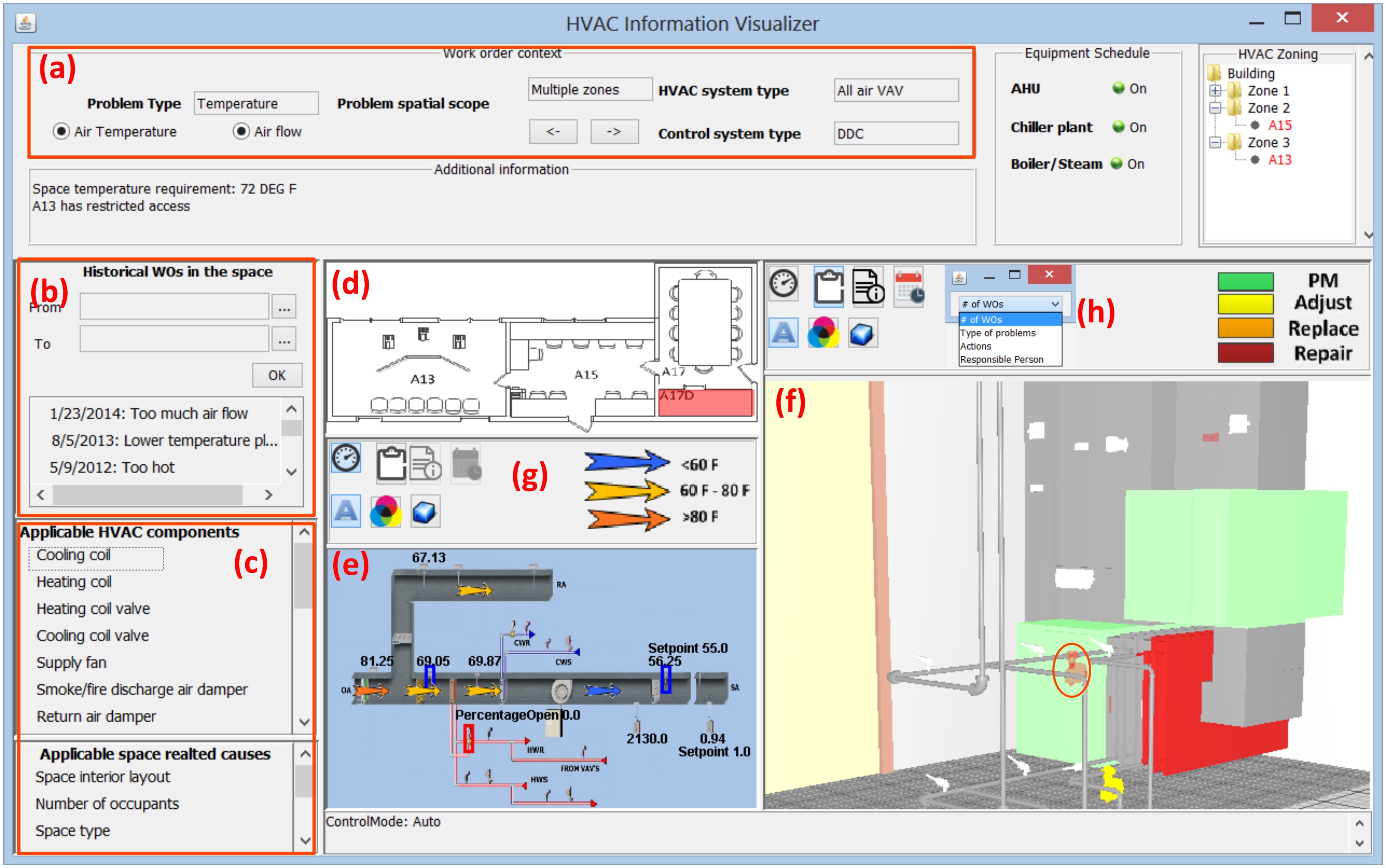
<table>
<tr><th colspan="2">Information</th><th>Selected visualization techniques</th></tr>
<tr><td rowspan="2">HVAC component static information</td><td>Location</td><td>Both floor plan marked room ID and 3D model</td></tr>
<tr><td>Control relationships</td><td>Schematic diagram highlighting relevant components</td></tr>
<tr><td colspan="2">HVAC component dynamic information</td><td>Schematic diagram + Text overlay/annotation
Schematic diagram + Color coding
Schematic diagram + Symbol/metaphor
3D model + Color coding
3D model + Symbol/metaphor</td></tr>
<tr><td colspan="2">HVAC component historical information</td><td>Schematic diagram + Text overlay/annotation
Schematic diagram + Color coding
Schematic diagram + Symbol/metaphor
3D model + Color coding
3D model + Symbol/metaphor</td></tr>
</table>

Since different visualization techniques were identified to show the spatial contexts, a multi-view visualization technique is needed to combine these spatial contexts as different views, as discussed in the next section.

4.3.4 Implementing a high-fidelity prototype

High-fidelity prototyping aims to develop user interface prototypes that are almost as functional as the final product. It requires longer time and higher cost to implement and thus is usually used at the last stage of user interface design process when users' requirements are already obtained from earlier user studies (Retting 1994). The high-fidelity prototype in this research study is implemented based on the results from the low-fidelity prototyping user studies presented in the last section.

As shown in Table 20, floor plan, HVAC system schematic diagram and 3D model are required to visualize the spatial information for different information items, and thus the techniques of multi-viewing is used to integrate these multiple views of the spatial contexts. The semantic information items are encoded in the spatial contexts according to the visualization requirements (Table 20). The information is visualized as shown in Figure 44. The interface displays all information that HVAC mechanics need for troubleshooting for a given work order, however the information items that do not require visualization, per the requirements of visualization discussed in the background section, are shown in text boxes. These are the work order information, displayed at the top [Figure 44(a)] of the interface, and the complaints log at the top of the left column [Figure 44(b)]. Identified applicable causes are listed at the left column [Figure 44(c)], which includes applicable HVAC components and space related causes. By selecting different components in the list, the visualization views [Figure 44(d), 6(e) and 6(f)] will display the location, control relationships, dynamic information and historical information for the selected component. In Figure 44, a heating coil valve was selected. The floor plan view highlights the room where the heating coil valve locates [Figure 44(d)], and 3D model view also highlights the component [Figure 44(f)] to show its exact location in the room. The two sensors that are related with the control of the heating coil valve are highlighted in the schematic diagram view [Figure 44(e)]. By default, the visualization interface displays dynamic data using schematic diagram augmented with symbol indicating the temperature readings [Figure 44(e)] (i.e., option 3c, with the highest score in all options for dynamic information), and displays the historical information of the valve using 3D model color-coded by the type of remedial actions [Figure 44(f)] (i.e., option 4e, the highest score in all options for maintenance history). Users can change the default visualization settings for dynamic information and maintenance history information to customize the visualization options that they prefer, by using the provided menus [Figure 44(g) and (f)]. Moreover, users can select what specific maintenance history information they want to see using the dropdown menu [Figure 44(h)].



Note: (a) Work order context; (b) Complaints log (c) Applicable cause; (d) Floor plan view; (e) Schematic diagram view; (f) 3D model view; (g) and (h) Menus to configure information and visualization options

Figure 44. Integrated multi-view visualization environment

4.3.5 Protocol for user studies with the high-fidelity prototype

In order to evaluate the high-fidelity prototype, six HVAC mechanics from an FM group participated in another round of user studies again. The objective of the user studies is to evaluate if there is performance improvement for HVAC mechanics to troubleshoot HVAC related problems using the developed prototype, compared with the current practice. Therefore, instead of simply asking users' opinions and preferences, tasks for troubleshooting HVAC related problems were given to the users and the time consumption was used as the quantitative metric to measure users' performances.

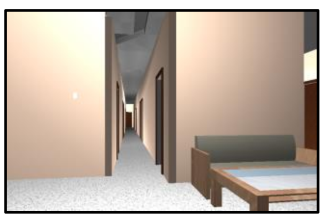
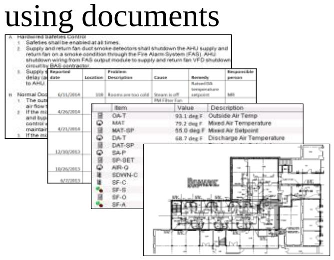
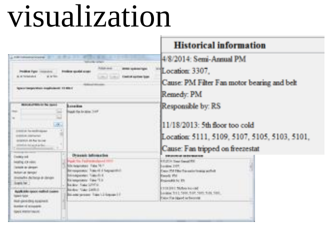
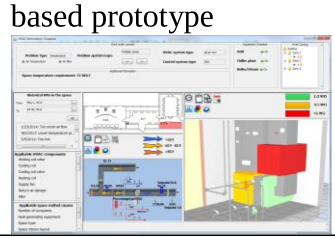
Three scenarios were designed in order to compare HVAC mechanics' performances under different settings of getting access to required information. The task objective for all three scenarios is to identify the cause for the assigned work order with HVAC related problem. The work orders assigned to HVAC mechanics for the three scenarios, the snapshots of the facilities, and the different settings of information support is provided by Table 21. The first scenario is the baseline, where HVAC mechanics need to complete the task with information support as that in the current practice. The information sources provided to participants include a set of drawings for the facility, the control logics description for the HVAC system, the snapshot of the dynamic data from BAS system for the HVAC system, and the document of historical maintenance records. These sources provide information of location, control relationships, dynamic information and maintenance history information, respectively.

The second scenario represents the information support using the developed prototype displaying required information in text-based format without any visualization. The third scenario represents the information support using the integrated visualization environment as shown in

Figure 44. The only difference between the prototypes for the second scenario and the third scenario is that the former displays the location, control relationships, dynamic information and maintenance history in text, while the latter visualize the aforementioned information. The reason to have the second scenario is to differentiate the performance variations for HVAC mechanics with information support versus with visualization-based information support, in order to understand if there is performance improvement for HVAC mechanics to have the information integrated and provided, and if there is further improvement when the generated information being visualized.

All of the three work orders have the same work order contexts to eliminate any bias with change in work order contexts in the results: they are all associated with a temperature problem, happened in multiple zones, and the HVAC systems serving the affected rooms are of all-air VAV type. Three different facilities were used for the three scenarios in order to eliminate the factor that participants are getting familiar with the space and the HVAC system in the course of doing tasks and perform better in the subsequent tasks. The reason to design the three work orders with the same context is to make sure they have the same level of difficulty for HVAC mechanics. Since it is not feasible to intentionally break an HVAC component in the real world and ask HVAC mechanics to identify the cause, virtual environments were used to simulate the facilities for the assigned work orders. Virtual environment, or virtual reality, uses computer generated 3D graphics to simulate a real world environment. The objective of using virtual environment in this study is to create an experimental environment where HVAC mechanics can do the tasks of troubleshooting HVAC related problems as they cannot do these in real world settings with real faults in HVAC systems. The virtual environments included buildings with the reported space area in the work orders, and the HVAC system serving the space with detailed components and ductwork modeled. Users could perform the inspections of the spaces and the HVAC systems as they do in real world, such as checking the setpoint of a thermostat, and checking to see if a component works properly, until the right cause is identified. The virtual environments were developed using a game engine with 3D models exported from a commercial building information model development tool.

Table 21. Summary of the scenario settings for the user studies

<table>
<tr><td>Task objective</td><td colspan="3">Identify the cause for the assigned work order with HVAC related problem</td></tr>
<tr><td>Scenario</td><td>Scenario 1</td><td>Scenario 2</td><td>Scenario 3</td></tr>
<tr><td>Work order</td><td>Location: Building A-118 wing
Problem: The entire 118 wing is too hot
</td><td>Location: Building B-5101-5109
Problem: Rooms are the corridor 5100 are too hot
</td><td>Location: Building C-A13,A15,A17
Problem: The three rooms are too cold
</td></tr>
<tr><td>Information support</td><td>Information provided using documents
</td><td>Information provided using prototype without visualization

</td><td>Information provided using visualization-based prototype
</td></tr>
</table>

At the beginning of each user study, I explained the objective and procedure of this study, and answered the participants' questions until they indicated they were comfortable to start and their time of completing the tasks would be recorded. In order to eliminate the effect of different participants' computer skills on the time consumption to use the virtual environments and the developed prototypes, I was responsible for navigating in the virtual environments, interacting with different components, and configuring the visualization-based prototype based on the participants' requests.

4.3.6. Evaluation results and discussions

The time that each participant used to complete the assigned tasks for three scenarios were recorded and the statistical results are provided in Figure 45. Based on the results, it is found that there is a reduction in completion time by 35% (in medium) for HVAC mechanics using prototype which integrates and provides the required information (scenario 2), compared with searching for information from documents as in the current practice (scenario 1), and there is further reduction by 23% (in medium) when the required information is visualized (scenario 3). Visualization of the required information reduces the completion time by 58% compared with the searching information from document. In addition, statistical test (t-test) shows that there is significant ($P<0.05$) time reduction for both of the prototypes (with and without visualization), compared with the current practice.

What also worth mentioning here is that because virtual environments were used to simulate the real-world facilities settings, the time spent in the virtual world would be different from that in real world hence utilization of relative improvements in the time as compared to absolute values in comparison of the options would be more logical here. In this user study experiment, the time in the virtual world is shorter than that in the real world for a couple of reasons. First, the travel time in the virtual world is shorter because the walking speed is set up to be faster than normal walking speed, so that participants do not waste too much time in the study on walking in the virtual world. Second, the time spent on inspecting a component is not considered in the virtual world because the focus of the use study is to measure HVAC mechanics' decision-making time on which components to check and order to check components, not their speed to check if a component is working properly.

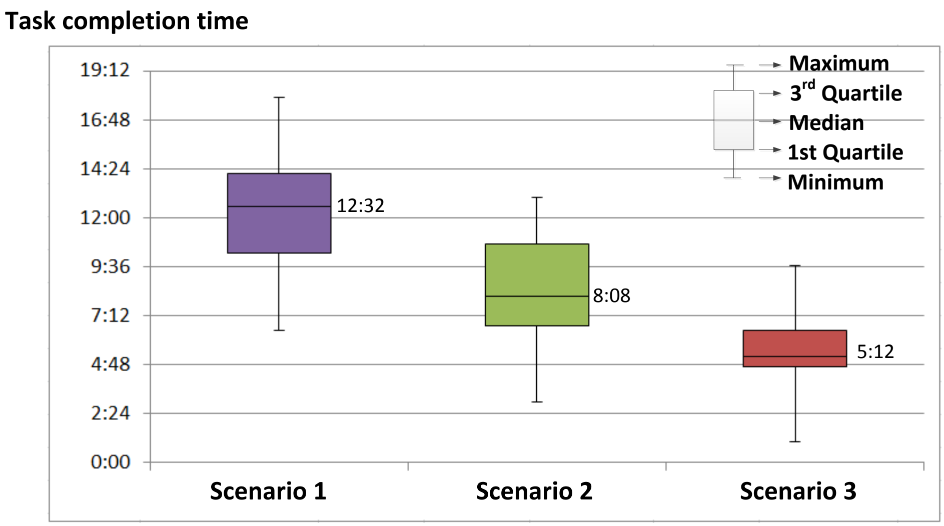


Figure 45. Statistical results of time (in minutes) to troubleshoot a given HVAC problem

Observations during the user studies and interviews afterwards showed that the reason behind the improvement of HVAC mechanics' working efficiency in the second scenario is mainly because the applicable causes are provided and required information is automatically integrated, which saves time for HVAC mechanics as compared to manually identifying applicable causes and searching through different sources for the required information. The further efficiency improvement obtained by using visualization-based information support can be attributed to three reasons:

(1) Less mental effort to comprehend the displayed information. When the required information is provided in a text-based format, HVAC mechanics need to read and understand the meaning of the information. Visualizing the required information enables HVAC mechanics to comprehend

the information more efficiently by the visual aids. For example, by visualizing the air temperature readings in an HVAC system, HVAC mechanics can understand the temperature control statues at a glance.

(2) Less time to locate HVAC components. HVAC components are usually hidden above ceilings, behind walls, or in mechanical rooms that are far from the served rooms, and thus it is challenging for HVAC mechanics to quickly locate the components they want to check when they are not familiar with the spaces and the HVAC system at hand. In the second scenario when the location information is shown in a textual form, only the ID of the room where the component locates can be provided, but HVAC mechanics still need to spend extra time to locate the specific component when they are in the room. When using visualization techniques, the 3D model gives more precise location information by highlighting the components and also shows the surrounding space and equipment. This way of visualization enables HVAC mechanics to quickly match and locate the components in real world.

Interviews after the user studies also showed that having the linkage between schematic diagram view and 3D model view (i.e., when selecting a component, the component is highlighted in the schematic view, and the 3D view automatically zooms in to the component) could help HVAC mechanics quickly locate a component. Examples of the comments from the participated HVAC mechanics are:

"Many times when I looked at the schematic diagram, I know there is such a sensor existing but I don't know where exactly it is. The 3D view can help me quickly locate the component."

"Schematic diagram details the configuration of an HVAC system and the relative location of components, for example, this sensor appears before this damper, but does not reflect the actual location. The 3D view is good to show where they are."

Schematic diagram has the advantage of abstracting all HVAC components in a system and their spatial relationships in one view based on their relative positions, through which HVAC mechanics can quickly have a holistic understanding about the configuration of the system, but the disadvantage is that it does not reflect the actual layout of the system and location of the components. For example, a schematic diagram can show that there is a discharge air damper in an HVAC system, and with that HVAC mechanics only know that the damper is somewhere in the ductwork and they still need to trace the ductwork on field to find the component or they need to refer to mechanical drawings. On the other hand, 3D model shows the real layout of the system and the location of the components, but because only a specific viewport of the 3D model can be seen at a given time from the computer screen, it limits HVAC mechanics' understanding of the entire system at a glance. It takes time and requires skills to manipulate the 3D model, such as rotate, zoom in/out, and pan, to see the model from different viewports in order to understand the entire system. When there is a linkage between the two views, HVAC mechanics not only have a holistic understanding about the configuration of the system, but also have the actual layout of the system and see the location of components in the real world, which is very convenient for them to quickly match and locate a component.

(3) More use of HVAC component historical information. Visualizing the required information encourages HVAC mechanics to use the information that they may not notice before. Maintenance history of HVAC components is agreed by HVAC mechanics to be required and valuable information to know (Yang and Ergan 2014a). However, it was observed from the user

studies that HVAC mechanics are not used to referring to historical maintenance records during the troubleshooting process. None of the users in the first scenario used the document that provided the maintenance records. It is because in the current practice, maintenance history is not formally captured and usually stored as tacit knowledge of HVAC mechanics, who are typically responsible for specific buildings and thus may know the maintenance history of the spaces and HVAC systems over years of work. By referring to their previous experience and knowledge, HVAC mechanics, who are familiar with a building and its maintenance history, usually can identify causes for reported problems more quickly than HVAC mechanics who are new to a building. Nonetheless, because they are not used to referring to maintenance records, they do not actively seek valuable information from maintenance history. When asked about why not used the provided maintenance records in the first scenario, an example of comment is:

"I forgot the check this (i.e., the maintenance records). If I knew this earlier, I could find the cause much faster."

It is observed that even though none of the participants used maintenance history in the first scenario, there was a trend in the user studies that more participants used maintenance history when the information is provided and visualized.

4.3.7 Conclusion

This study provides a holistic understanding of the impact of different forms of information support interfaces on efficiencies of HVAC mechanics while they work on troubleshooting of HVAC related work orders. The contribution of this study is the design and evaluation of an integrated multi-view visualization platform to support troubleshooting of HVAC related problems. This study constitutes a comprehensive work where a variety of applicable visualization techniques were evaluated to design the visualization platform without preselecting any de-facto visualization forms. The process of designing the visualization platform consisted of five steps: (1) Identifying what information to visualize and applicable visualization techniques, (2) implementing low-fidelity prototypes for the visualization alternatives, (3) getting users' feedback about the alternatives, (4) implementing high-fidelity prototype based on users' feedback; (5) evaluating the high-fidelity prototype by user studies. The final evaluation results showed that the developed prototype of the integrated visualization platform can increase the efficiency of HVAC mechanics compared with that of the current practice around 60%. 35% of the time is saved because the required information is automatically integrated and retrieved for HVAC mechanics, and another 23% time saving is achieved due to the benefits of visualizing the required information.

The results of this study can be used by computer aided FM solution and BAS vendors to incorporate into their products when designing the user interfaces for HVAC maintenance purposes. FM industry practitioners can also refer to the findings to evaluate commercial solutions.

Chapter 5. Conclusion and future work

This chapter presents a summary of the contributions of the research work presented in this thesis, with discussions of the practical implications and future work.

5.1 Contributions

This research study has three main contributions: (1) Identification of general domain information for troubleshooting of HVAC related problems and the characteristics of work orders that affect information requirements; (2) Representation schema and reasoning mechanisms to enable automatic identification of applicable causes and retrieval of required information for a given work order; and (3) Evaluation of the efficiency improvement of the decision-making process during tasks of troubleshooting HVAC related problems using visualization platform.

5.1.1 Contribution 1: Identification of general domain information for troubleshooting of HVAC related problems and the characteristics of work orders that affect information requirements

The study presented in Chapter 2 highlighted the challenges in the current practice for troubleshooting of HVAC related problems due to lack of systematic approaches to enable the identification of what specific facility information HVAC mechanics should check for a given work order. The first step towards developing such a systematic approach is to understand how the required information to troubleshoot a given problem changes and what types of facility information HVAC mechanics need in general. Through several elicitation techniques with 28 HVAC mechanics from three different FM groups, I identified 40 information requirements of

HVAC mechanics to troubleshoot HVAC related problems and grouped them into 5 categories: (1) HVAC related complaint logs; (2) HVAC system/ component static information; (3) HVAC system/component dynamic information; (4) HVAC system/component historical information; and (5) space related information. Moreover, I also identified 5 characteristics of work orders that HVAC mechanics consider when determine what component to check and information to know: (1) type of the reported problem; (2) spatial scope of the reported problem; (3) type of the HVAC system; (4) type of the control system; and (5) time pattern of the reported problem. The set of information requirements and characteristics of work orders serve as the basis for developing a formal approach to provide information support for troubleshooting of HVAC related problems.

5.1.2 Contribution 2: Representation schema and reasoning mechanisms to enable automatic identification of applicable causes and retrieval of required information for a given work order

Based on the identified information requirements identified in Chapter 2, I developed a representation schema that enables integrated representation of HVAC troubleshooting related information. Using the developed representation schema as the underlying data structure, I also developed an approach composed of a set of reasoning mechanism to (a) generate a work order's context through a graph-based reasoning and standard HVAC design constraints, (b) automatically identify a generic set of applicable causes based on the given work order's context, and (c) automatically refine the identified generic set of causes by matching them to facility specific instances and retrieve relevant information. This approach provides HVAC mechanics a customized set of causes for a given HVAC related problem, in order to reduce the search space and the possibility of neglect of root causes. It also retrieves relevant information for HVAC mechanics, so that they can use the information as evidences to determine the real cause among applicable causes.

5.1.3 Contribution 3: Evaluation of the efficiency improvement of the decision-making process during tasks of troubleshooting HVAC related problems using visualization platform

The study presented in Chapter 4 provides a holistic understanding of the impact of different forms of information support interfaces on the efficiencies of troubleshooting of HVAC related work orders. This study constitutes a comprehensive work where a variety of applicable visualization techniques were evaluated to design the visualization platform without preselecting any de-facto visualization forms. The process of designing and evaluating the visualization platform consisted of five steps: (1) Identifying what information to visualize and applicable visualization techniques, (2) implementing low-fidelity prototypes for the visualization alternatives, (3) getting users' feedback about the alternatives, (4) implementing high-fidelity prototype based on users' feedback; (5) evaluating the high-fidelity prototype by user studies. The final evaluation results showed that the developed prototype of the integrated visualization platform can increase the efficiency of HVAC mechanics compared with that of the current practice around 60%.

5.2 Practical implications

This research has possible practical implications on different practitioners: HVAC mechanics, facilities managers, computer-aided FM solution vendors and researchers.

(1) Providing references for determining the information that needs to be captured and stored for facility maintenance

Currently the lack of information support is a known issue in the FM industry, and as a result maintenance staff has to stay idle waiting for information or spend time on information verification. The identified information requirements for HVAC mechanics help facilities managers to understand what information needs to be captured, stored and made available to their maintenance staff in order to improve their performances. Facilities managers can also use the identified information and visualization requirements as basis in selecting the commercial tools.

(2) Providing the information support for HVAC mechanics on troubleshooting HVAC related problems

It is known that troubleshooting HVAC related problems is challenging because there are too many possible causes and a variety of information items need to be collected to determine the real cause. HVAC mechanics usually have to make decisions with limited understanding of the facility and access to required information, and as a result the responses to occupants' complaints are delayed and the root causes are left undiscovered. The developed approach to automatically identify customized set of possible causes and retrieve relevant information for a given work order can help HVAC mechanics to get access to sufficient information support and perform efficient troubleshooting.

(3) Supporting the future FM software development

The information and visualization requirements identified in this research study, and the user study results can provide the references for computer-aided FM software vendors to consider when developing the next generation of products. This study has shown that the HVAC mechanics' work efficiency can be improved when they have sufficient information support. FM software vendors can extend the services to larger scope of maintenance activities. Moreover, the developed visualization platform interfaces can be easily commercialized by the vendors and incorporated into their products.

5.3 Future work directions

This section summarizes several possible future research directions:

(1) Developing the functionality for maintenance report

The developed approach can be extended to help capturing accurate maintenance history that the current commercial CMMS cannot do. As identified in this research, maintenance history that needs to be captured include *the type of the problem* (what happened), *time stamp* of the complaint (when it happened), *the cause* of the problem (why it happened), *the remedy actions taken* such as replace, repair and assess (what was done), *responsible mechanic* that worked on the order (who solved it) and if *follow up actions* are needed. What the current CMMS lack is to capture the exact cause of the reported problems at component level and what was done to the completed or not, but not what was done to solve the problem and it is hard to keep track of the maintenance status at the asset component level. Knowing the maintenance status at component level can help facility managers to better plan maintenance activities and may enable the identification of unobvious problems. For example, if a fan belt has been changed in a corrective maintenance activity in a short time before its scheduled preventive maintenance time, the preventive maintenance can be cancelled; if the same type of components from a manufacturer has high failure rate, maybe it's time to consider changing the supplier.

(2) Developing approaches to prioritize the applicable causes for a given work order

The approach as presented in Chapter 3 can automatically identify applicable causes for a given work order, however, the causes are not ranked and it's up to HVAC mechanics to decide the order to do the investigation. It is possible that the applicable causes can have different probability of being the real cause in a specific facility. Even HVAC systems with exact same configurations under different operation and maintenance conditions can have different failure modes. For example, an exhaust fan in a kitchen space has higher probability of failure for an air flow problem than the same type of exhaust fan serving an office space, because the heavy daily operation load. The future research can look into the factors that affect the probability of different causes for a problem in a specific facility and provide prioritized list of the applicable causes. Moreover, when the approach is put into practice and the identified causes for every work order are recorded, it will compose a valuable knowledge base on which machine learning or data mining approaches can be used to analyze the probability of applicable causes for different types of facility conditions.

(3) Extending the scope of the research to other type of corrective maintenance work

Though this research focuses on the corrective maintenance work with HVAC related problems, it provides a formal approach to leverage BIM to address the issue of lack of information support in FM industry and can be extended to the maintenance work on other building systems, such as electrical and plumbing related problems. Future work can study in terms of (a) the information requirements for other maintenance work; (b) the characteristics of the work orders for other building systems and develop the mapping with the applicable causes and information requirements.

(4) Developing the functionality to allow users to define new design constraints for an HVAC component

The design constrains that were used in RQ2 to differentiate HVAC components of the same type with different functions were developed based on standard components as documented in HVAC handbooks. However, there could be variations or customizations of HVAC components used in real world, which would result in different sets of constraints from those described in the handbooks. Also, it is possible that new types of HVAC components being invented and used in the industry, which require the definition of their design constraints. Therefore, future work can develop the functionality to allow users to define new design constraints for HVAC components.

(5) Evaluating the integrated visualization environment under dynamic conditions

The developed integrated visualization environment was evaluated with the assumption that the data provided is static at a given time point. The data involved, such as sensor readings, control commands, and HVAC maintenance history, has dynamic nature, which means that the data value can be changing with time. When the data is changing, the usability of the visualization interfaces can be affected in term of how well the users can comprehend the dynamic data. This factor is currently not considered in the user studies, and it would an interesting future research direction.

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Appendix A. The mapping between causes library and work order contexts

Table A1. Library of causes mapped with types of problem

Causes	**Types of problem identified from shadowing**	**Types of problem identified from interviews and focus groups**	**Types of problem identified from literature** (Fletcher 1999a; Fletcher 1999b; Hyvärinen and Kärki 1996; Friedman 2004; Budaiwi 2007)
Thermostat	Temperature	Temperature	Temperature Air flow
Supply diffuser	Temperature, Air flow Noise	Temperature, Air flow Noise	Temperature Air flow Noise
Return grille	Air flow Noise	Air flow Noise	Temperature Air flow Noise
Exhaust grille	Humidity	Air flow Noise	Temperature Air flow Noise
Zone damper (VAV, mixing, bypass)	Temperature Air flow	Temperature, Air flow Noise Odor	Temperature Air flow Odor Noise
Reheat coil	Temperature	Temperature Leaking	Temperature
Reheat valve	Temperature	Temperature Leaking Noise	Temperature
Radiator	Temperature		Temperature
Radiator valve	Temperature	Noise	Temperature
Terminal humidifier	Humidity	Humidity	Humidity
Terminal cooling coil	Temperature	Temperature Air flow Leaking Odor	Temperature
Terminal cooling coil valve	Temperature	Temperature Leaking Noise	Temperature
Terminal heating coil	Temperature	Temperature Air flow Leaking Odor	Temperature

Terminal heating coil valve	Temperature	Temperature, Leaking, Noise	Temperature
Terminal fan	Temperature	Temperature Air flow Odor	Air flow Noise
Terminal filter	Temperature	Temperature Air flow Odor	Temperature Air flow Odor
OA intake	Odor	Odor	Odor
OA damper	Temperature, Humidity, Odor	Air flow, Humidity Noise Odor	Temperature Air flow Odor
Filter	Temperature, Odor	Temperature Air flow Odor	Temperature Air flow Odor
Heating coil		Temperature Air flow Leaking Odor	Temperature Air flow
Heating valve		Temperature Leaking Noise	Temperature
Cooling coil	Temperature, Humidity	Temperature Air flow Humidity Leaking Odor	Temperature Air flow
Cooling valve	Temperature, Humidity	Temperature Humidity Leaking Noise	Temperature
Central reheat coil		Temperature Air flow Leaking Odor	Temperature Air flow
Central reheat valve		Temperature Leaking Noise	Temperature
Supply fan	Temperature, Air flow	Temperature Air flow Odor Noise	Temperature Air flow Odor Noise

Return fan	Air flow	Temperature Air flow Odor Noise	Temperature Air flow Odor Noise
Exhaust fan	Air flow, Humidity	Temperature Air flow Odor Noise	Temperature Air flow Odor Noise
Fire damper		Temperature Air flow Odor Noise	Temperature Air flow Odor Noise
RA damper	Air flow	Temperature Air flow Odor Noise	Temperature Air flow Odor Noise
EA damper	Air flow	Temperature Air flow Odor Noise	Temperature Air flow Odor Noise
Face and bypass damper		Temperature Air flow Odor Noise	Temperature Air flow Odor Noise
Energy recovery device			Temperature Air flow
Central humidifier		Humidity	Humidity
Air compressor	Temperature	Temperature, Noise	
Pipe	Leaking	Leaking, Noise	Leaking
Space type change	Air flow	Temperature, Humidity	Temperature Odor
Addition of heat-generating equipment in space		Temperature	Temperature Air flow
Space occupant number change		Temperature	Temperature Air flow
Space lighting change			Air flow
Space interior walls/partitions change		Temperature	Temperature Air flow Odor

Table A2. Library of causes mapped with type of HVAC system and spatial scope

	HVAC components	**ASHRAE 2008**	**McDowall 2006**	**Kreider et al. 2001**	**Pita 1998**	**HVAC system 1 (Air+ radiator)**	**HVAC system 2 (VAV)**	**HVAC system 3 (Air+ FCU)**	**HVAC system 4 (CAV)**	**HVAC system 5 (Dual duct)**
Terminal unit components	Thermostat	All-air	All-air	All-air	All-air	√	√	√		√
	Supply diffuser	All-air	All-air	All-air	All-air	√	√	√		√
	Return grilles	All-air	All-air	All-air	All-air	√	√			√
	Exhaust grilles	All-air	All-air	All-air	All-air					
	Zone damper (VAV, mixing, bypass)	VAV; DualDuct	VAV; DualDuct	VAV; DualDuct	VAV; DualDuct	√	√			√
	Zone reheat coil	CAV; VAV	CAV; VAV	CAV; VAV	CAV; VAV	√	√			
	Zone reheat valve	CAV; VAV	CAV: VAV	CAV; VAV	CAV; VAV	√	√			
	Radiator	Radiator; Air-radiator	Radiator; Air-radiator		Radiator; Air-radiator	√				
	Radiator valve	Radiator; Air-radiator	Radiator; Air-radiator		Radiator; Air-radiator	√				
	Terminal humidifiers	All-air								
	Terminal fan	VAV; FCU	FCU		FCU		√	√		
	Terminal filter	All-air; FCU	FCU		FCU			√		

	Terminal cooling coil	FCU	FCU		FCU			√		
	Terminal cooling coil valve	FCU	FCU		FCU			√		
	Terminal heating coil	FCU	FCU		FCU			√		
	Terminal heating coil valve	FCU	FCU		FCU			√		
Centralized air handling components	OA intake	All-air	All-air			√	√	√		√
	OA damper	All-air	All-air	All-air	All-air	√	√	√		√
	Filter	All-air	All-air	All-air	All-air	√	√	√		√
	(Pre)Heating coil	All-air	All-air	All-air	All-air	√	√			√
	(Pre)Heating valve	All-air	All-air	All-air	All-air	√	√			√
	Cooling coil	All-air	All-air	All-air	All-air	√	√	√		√
	Cooling valve	All-air	All-air	All-air	All-air	√	√	√		√
	Central reheat coil	Dual-duct	Dual-duct	All-air	All-air					√
	Central reheat valve	Dual-duct	Dual-duct	All-air	All-air					√
	Supply fan	All-air	All-air	All-air	All-air	√	√	√		√
	Return fan	All-air	All-air	All-air	All-air	√	√	√		√
	Exhaust/relief fan	All-air	All-air	All-air						
	Exhaust/relief opening	All-air				√	√	√		√
	Return/mixed air damper	All-air	All-air	All-air	All-air	√	√	√		√
	Face and bypass				All-air					

	damper									
	Exhaust/relief air damper	All-air	All-air	All-air	All-air	√	√	√		√
	Smoke/fire damper			All-air		√				
	Central humidifier	All-air	All-air	All-air						
	Energy recovery device	All-air		All-air			√			

Appendix B. Java code snippet to generate Directed Acyclic Graph for HVAC systems

```
//…omitted some sections
	public HVACGraphsGenerator()
	{
		hvacGraph = new DefaultDirectedGraph<IfcDistributionElement, 
DefaultEdge>(DefaultEdge.class);
		hvacComponent = new ArrayList<IfcDistributionElement>();
		oaIntake = null;
		initialSpace = null;

		supplyMapList = new 
ArrayList<HashMap<IfcSpace,DefaultDirectedGraph<IfcDistributionElement, 
DefaultEdge>>>();
		returnMapList = new 
ArrayList<HashMap<IfcSpace,DefaultDirectedGraph<IfcDistributionElement, 
DefaultEdge>>>();
	}

	public void startGenerateGraph(ArrayList<IfcSpace> s)
	{
		reportedSpaces = new ArrayList<IfcSpace>(s);
		if(reportedSpaces.size()!=0)
		{
			spaceSupplyGraphMap = new 
HashMap<IfcSpace,DefaultDirectedGraph<IfcDistributionElement, DefaultEdge>>();
			spaceReturnGraphMap = new 
HashMap<IfcSpace,DefaultDirectedGraph<IfcDistributionElement, DefaultEdge>>();
			otherSpaces = new ArrayList<IfcSpace>();

			initialSpace = reportedSpaces.get(0);
			reportedSpaces.remove(0);
			generateHVACGraphs(initialSpace);
			traceOtherSpaces();

			supplyMapList.add(spaceSupplyGraphMap);
			returnMapList.add(spaceReturnGraphMap);

			ArrayList<IfcSpace> tempSpaces = new ArrayList<IfcSpace>();
			for(int i=0; i<reportedSpaces.size(); i++)
			{
				tempSpaces.add(reportedSpaces.get(i));
			}

			//check if other reported spaces are in the same system
			for(int i=0; i<reportedSpaces.size(); i++)
			{
				IfcSpace sp = reportedSpaces.get(i);
				if(otherSpaces.contains(sp)) //if other spaces in the same 
system at that for the initial space contain other reported spaces
				{
					tempSpaces.remove(sp);
				}
			}
```

```
				startGenerateGraph(tempSpaces);
			}
		}

		//find the HVAC components serving the space and store them in directed
acyclic graphs
		public void generateHVACGraphs(IfcSpace ifcSpace)
		{
			supplyLocalGraph = new DefaultDirectedGraph<IfcDistributionElement,
DefaultEdge>(DefaultEdge.class);
				returnLocalGraph = new
DefaultDirectedGraph<IfcDistributionElement, DefaultEdge>(DefaultEdge.class);
				localSupplyHVACComponent = new
ArrayList<IfcDistributionElement>();
				localReturnHVACComponent = new
ArrayList<IfcDistributionElement>();

		//get all IfcRelContainedInSpatialStructure related with the space
			SET<IfcRelContainedInSpatialStructure> relContainedInSpatial =
ifcSpace.getContainsElements_Inverse();

		//get all ifc products that are contained in the space
			SET<IfcProduct> products = null;
			Iterator<IfcRelContainedInSpatialStructure> iter1 =
relContainedInSpatial.iterator();
				while (iter1.hasNext())
				{
					products = iter1.next().getRelatedElements();
				}

		//among all ifc products that are contained in the space, get air terminals
				ArrayList<IfcAirTerminal> ifcDiffusers = new
ArrayList<IfcAirTerminal>();
				Iterator<IfcProduct> iter2 = products.iterator();
				while(iter2.hasNext())
				{
					IfcProduct currentProduct = (IfcProduct) iter2.next();

		if(currentProduct.getClass().getName().toString().endsWith("IfcAirTerminal"))
					{
						ifcDiffusers.add((IfcAirTerminal)currentProduct);
					}
				}

				if(ifcDiffusers.size()!=0)
				{
					//trace from the air terminals
					Iterator<IfcAirTerminal> iter3 = ifcDiffusers.iterator();
					while(iter3.hasNext())
					{
						IfcAirTerminal airTerminal = iter3.next();
						if(isSupplyAir(airTerminal))
						{
							hvacGraph.addVertex(airTerminal);
							supplyLocalGraph.addVertex(airTerminal);
```

```
                                        generateSupplyLocalGraph(airTerminal);

                                }
                                else if(isReturnAir(airTerminal) ||
isExhaustAir(airTerminal))
                                {
                                        hvacGraph.addVertex(airTerminal);
                                        returnLocalGraph.addVertex(airTerminal);
                                        generateReturnLocalGraph(airTerminal);
                                }
                        }
                        spaceSupplyGraphMap.put(ifcSpace, supplyLocalGraph);
                        spaceReturnGraphMap.put(ifcSpace, returnLocalGraph);
                }

        }

        //trace from supply air damper
        private void generateSupplyLocalGraph(IfcDistributionElement
ifcDistributionElement)
        {
                //Specify an element as input parameter
                SET<IfcRelConnectsPortToElement> relConnectsPortToElement =
ifcDistributionElement.getHasPorts_Inverse();
                Iterator<IfcRelConnectsPortToElement> iter1 =
relConnectsPortToElement.iterator();
                IfcDistributionElement element = null;
                ArrayList<IfcDistributionElement> newElement = new
ArrayList<IfcDistributionElement>();
                while(iter1.hasNext())
                        {
                                //find the port connected to the specified element
                                IfcRelConnectsPortToElement relTemp1 =
(IfcRelConnectsPortToElement)iter1.next();
                                IfcDistributionPort relatingPort =
(IfcDistributionPort)relTemp1.getRelatingPort();

                                //trace against the flow direction
        if(relatingPort.getFlowDirection().value.toString().equals("SINK"))
        {
                //find the other port
                SET<IfcRelConnectsPorts> relConnectsPort = null;
                SET<IfcRelConnectsPorts> connectedToPort =
relatingPort.getConnectedTo_Inverse();
                SET<IfcRelConnectsPorts> connectedFromPort =
relatingPort.getConnectedFrom_Inverse();
                if(connectedToPort!=null)
                {
                        relConnectsPort = connectedToPort;
                }
                else if(connectedFromPort!=null)
                {
                        relConnectsPort = connectedFromPort;
                }
                //find the element connected to the other port
```

```
            if(relConnectsPort!=null)
            {
                  Iterator<IfcRelConnectsPorts> iter2 = relConnectsPort.iterator();
                  if(iter2.hasNext())
                  {
                        IfcRelConnectsPorts relTemp2 = iter2.next();
                        IfcPort relatedPort = null;

      if(relTemp2.getRelatedPort().getGlobalId().toString().equals(relatingPort.getG
lobalId().toString()))
      {
            relatedPort = relTemp2.getRelatingPort();
      }
      else relatedPort = relTemp2.getRelatedPort();


      if(((IfcDistributionPort)relatedPort).getFlowDirection().value.toString().equa
ls("SOURCE"))
      {

      if(relatedPort.getContainedIn_Inverse().iterator().hasNext())
            {
                  //find the element
                  element =
relatedPort.getContainedIn_Inverse().iterator().next().getRelatedElement();

                  //add to global graph
      if((!hvacComponent.contains(element))&& !(element.getClass().getName().toStrin
g().endsWith("IfcPipeSegment")))
      {

      if(isSupplyAir(element))//not consider return air yet
      {
      hvacComponent.add(element);
      hvacGraph.addVertex(element);
      hvacGraph.addEdge(element,ifcDistributionElement);
      if(element.getClass().getName().endsWith("IfcAirTerminal"))
      {
            oaIntake = (IfcAirTerminal) element;
      }
      }
      else if(isReturnAir(element))
      {
      The last element in return route, which is connected to supply route
            lastReturnElement = element;
      }
      }
else if(hvacComponent.contains(element))
      {
            hvacGraph.addEdge(element,ifcDistributionElement);
      }

      //add to local graph
```

```
        if(!localSupplyHVACComponent.contains(element)
&& !element.getClass().getName().toString().endsWith("IfcPipeSegment"))
        {

        if(isSupplyAir(element))
                {

        newElement.add(element);

        localSupplyHVACComponent.add(element);

        supplyLocalGraph.addVertex(element);

        supplyLocalGraph.addEdge(element,ifcDistributionElement);
                }
        }
        else if(localSupplyHVACComponent.contains(element))
        {
                supplyLocalGraph.addEdge(element,ifcDistributionElement);
        }

     }
   }

}
}
}

}

        for(int i=0; i<newElement.size();i++)
        {
                generateSupplyLocalGraph(newElement.get(i));
        }
}

//…omitted some sections
```

Appendix C. Java code snippet to generate a work order context

```
private void spatialScopeDefiner(ArrayList<IfcSpace>
reportedSpaces,ArrayList<HashMap<IfcSpace,DefaultDirectedGraph<IfcDistributionElement,
DefaultEdge>>> sm,
ArrayList<HashMap<IfcSpace,DefaultDirectedGraph<IfcDistributionElement, DefaultEdge>>>
rm)
	{
		else if(sm.size()>1)
		{
			woContext.problemSpatialLevel =
ProblemSpatialLevelEnum.MULTIPLESYSTEMS;
		}
		else if(sm.size()==1 && rm.size()==1)
		{
			n=0; //# of spaces which do not have damper or coil
			zones = new ArrayList<ArrayList<IfcSpace>>();
			diffCentralVSLocalHelper(sm.get(0),rm.get(0));
			filterMultiZoneSpace(reportedSpaces);

			if(n==localSupplyComponentsMap.size())
			{
				woContext.problemSpatialLevel =
ProblemSpatialLevelEnum.SINGLESYSTEM;
			}
			else
			{
				boolean isSingleZone = false;

				for(int i=0; i<zones.size(); i++)
				{
					int m=0;
					ArrayList<IfcSpace> currentZone = zones.get(i);
					for(int j=0; j<reportedSpaces.size(); j++) //spaces
are the reported spaces
					{
						IfcSpace currentSpace = reportedSpaces.get(j);
						 if(currentZone.contains(currentSpace))
						 {
							m++;
						 }
					}
					if(m==reportedSpaces.size()) //if all reported
spaces are in the same zone
					{
						isSingleZone = true;
					}
				}

				if(isSingleZone)
				{
					woContext.problemSpatialLevel =
ProblemSpatialLevelEnum.SINGLEZONE;
				}
```

```
                        else
                        {
                                woContext.problemSpatialLevel =
ProblemSpatialLevelEnum.MULTIPLEZONES;
                        }
                }
        }

    }

    private void hvacTypeDefiner(ArrayList<IfcSpace>
spaces,ArrayList<HashMap<IfcSpace,DefaultDirectedGraph<IfcDistributionElement,
DefaultEdge>>> sm,

ArrayList<HashMap<IfcSpace,DefaultDirectedGraph<IfcDistributionElement, DefaultEdge>>>
rm)
    {
        HVACTypeEnum type1 = null;
        HVACTypeEnum type2 = null;
        ArrayList<IfcSpace> spaceType1 = new ArrayList<IfcSpace>();
        ArrayList<IfcSpace> spaceType2 = new ArrayList<IfcSpace>();

        if(sm.size()==1)
        {
            for(int i=0; i<spaces.size(); i++)
            {
                IfcSpace space = spaces.get(i);
                HVACTypeEnum currentType =
hvacTypePerSpace(space,localSupplyComponentsMap.get(space));

                if(type1==null)
                {
                    type1 = currentType;
                    spaceType1.add(space);
                }
                else if(type1 == currentType)
                {
                    spaceType1.add(space);
                }
                else if(type1 != currentType)
                {
                    if(type2==null)
                    {
                        type2 = currentType;
                        spaceType2.add(space);
                    }
                    else if(type2==currentType)
                    {
                        spaceType2.add(space);
                    }
                }
            }
            if(spaceType2.size()==0)
            {
                //System.out.println(type1.getName());
```

```
                        woContext.hvacType = type1;

                        if(type1==HVACTypeEnum.AIRWATERFCU)
                        {
                              if(spaces.size()==1)
                              {
                                    woContext.problemSpatialLevel =
ProblemSpatialLevelEnum.SINGLEZONE;
                              }
                              else if(spaces.size()>1)
                              {
                                    woContext.problemSpatialLevel =
ProblemSpatialLevelEnum.MULTIPLEZONES;
                              }
                        }
                  }
                  else
                  {
                        System.out.println("Spaces have mixed types of HVAC
system");
                  }
            }
      }

//…omitted some sections
```

Appendix D. User interface to edit library of causes and the mapping between work order contexts

Users can select a specific cause stored in the library [Figure D (a)], view its associated work order contexts [Figure D (b)], and add new work order contexts if necessary [Figure D (c)]. Users can also define new HVAC component in the cause library [Figure D (d)].

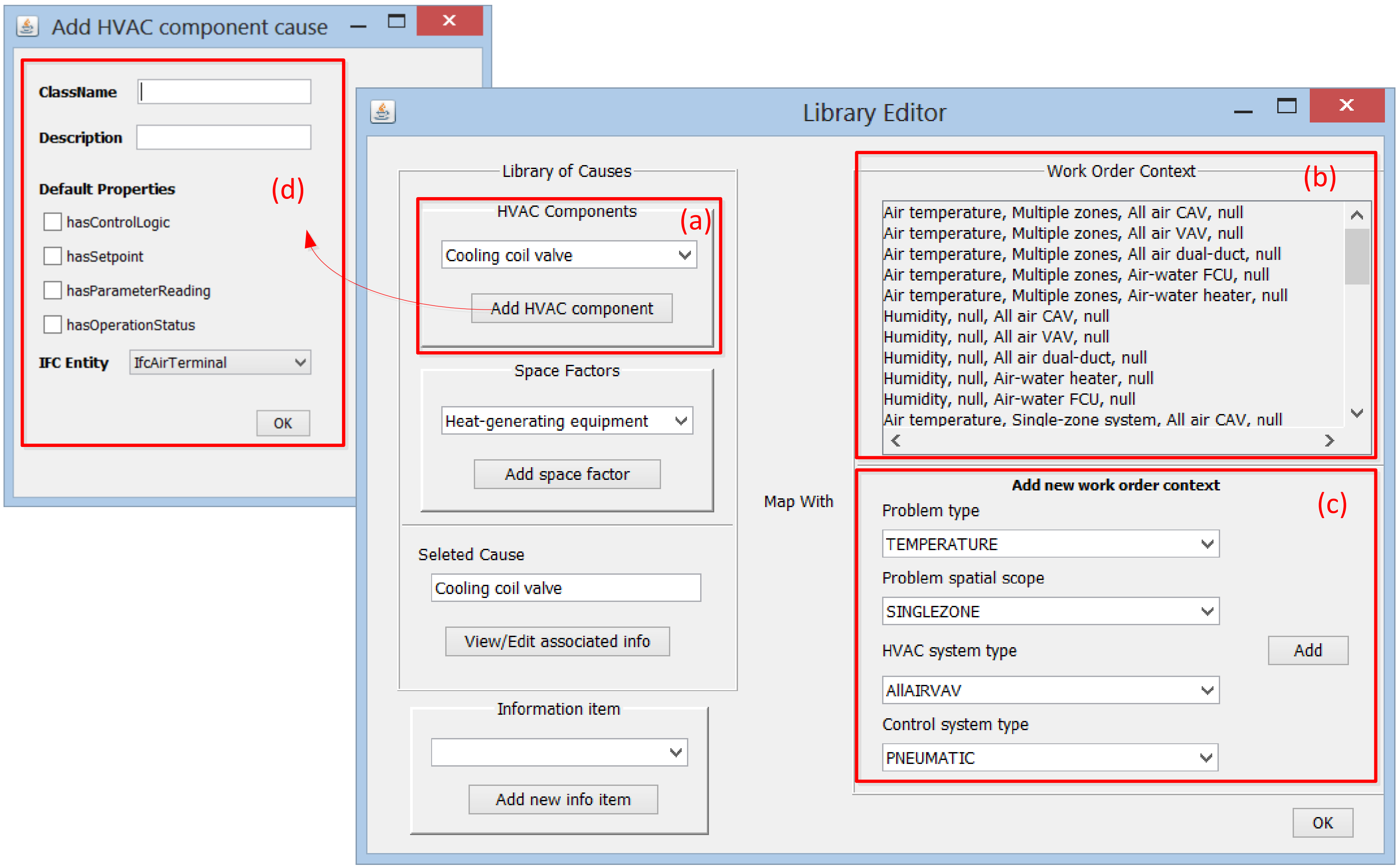

Figure D. User interface to edit library of causes and the mapping between work order contexts

Appendix E. Snapshots of virtual environments used in Chapter 4

Scenario 1:

Figure E1. Snapshot of the occupied rooms in virtual environment used in scenario 1

Figure E1. Snapshot of the mechanical room in virtual environment used in scenario 1

Scenario 2:

Figure E3. Snapshot of the occupied rooms in virtual environment used in scenario 2

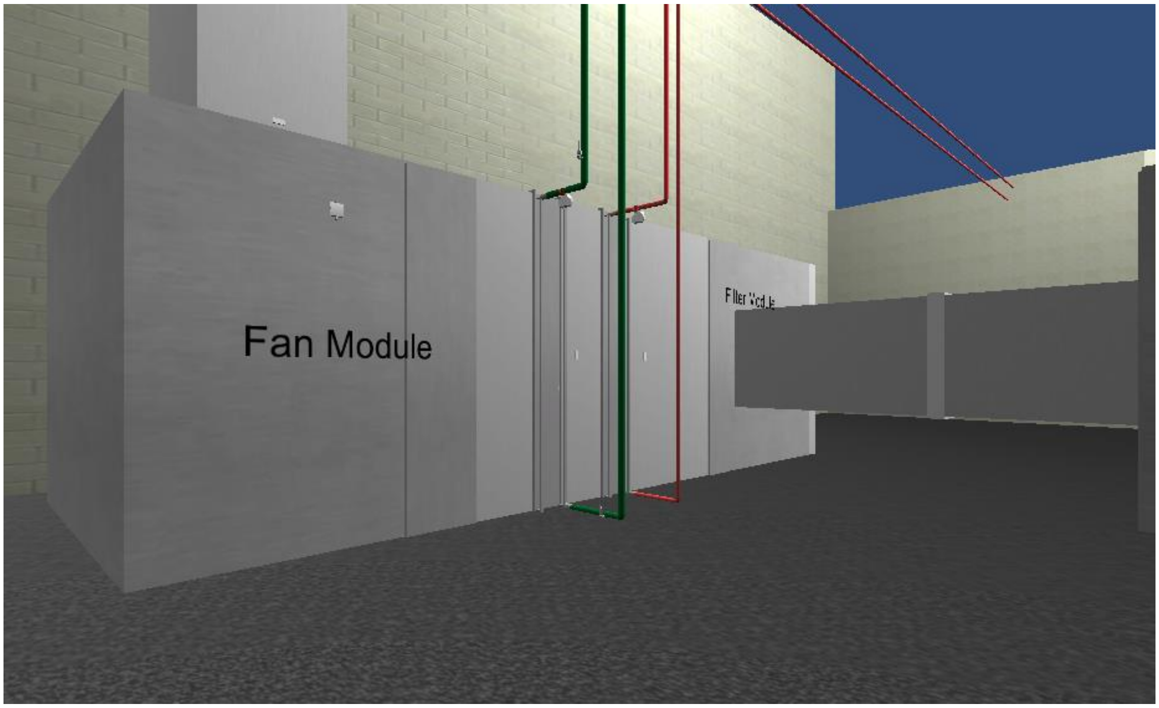

Figure E4. Snapshot of the mechanical room in virtual environment used in scenario 2

Scenario 3:

Figure E5. Snapshot of the occupied rooms in virtual environment used in scenario 3

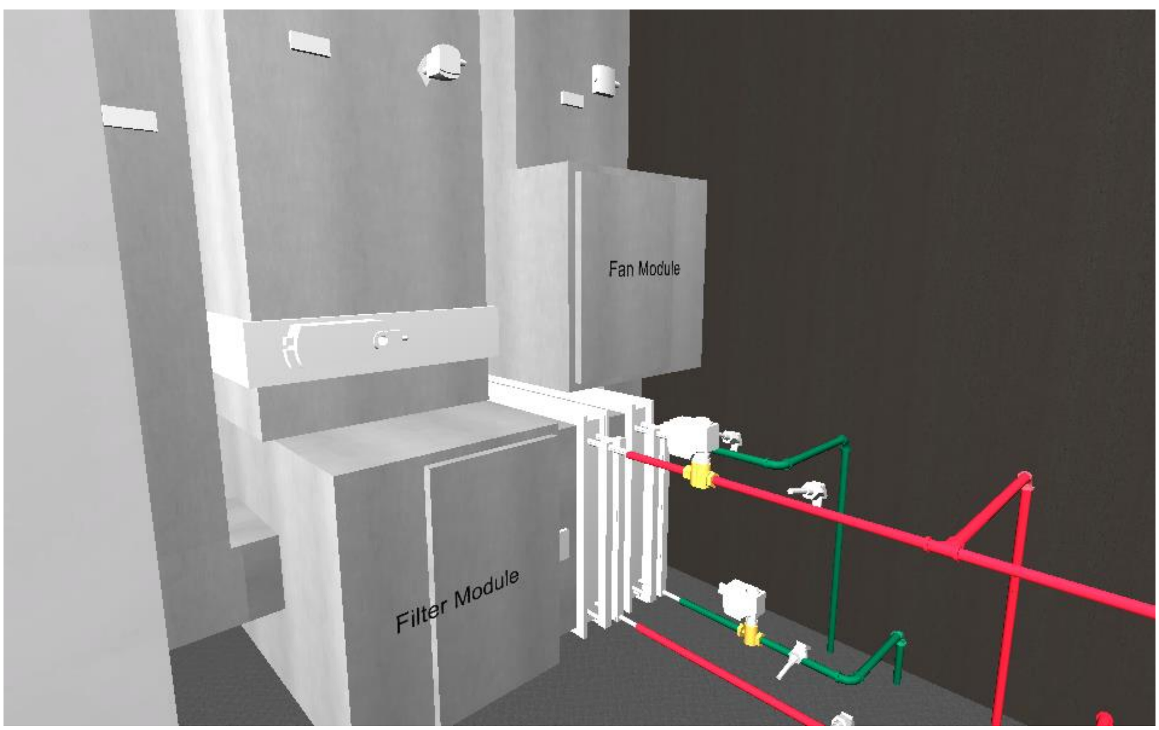

Figure E6. Snapshot of the mechanical room in virtual environment used in scenario 3

Appendix F. Structure of the csv files for inputs of work order history and space information

```
//Structure of the csv files for inputs of work order history
```
month, date, year, description, cause, component ID, remedial action, responsible person, problem type, need for follow-up

```
//Examples of rows in the csv file for inputs of work order history
```
8,5,2013,422,Lower temperature please,Thermostat,72773,Adjust,BK,Temperature,FALSE

12,20,2012,997,Semi-Annual PM,PM Filter Fan motor bearing and belt,40045;45858,PM,RS,PM,FALSE

7,9,2012,963,Too cold in the room, bad reheat valve,29852,Replace,MJ,Temperature,FALSE

6,30,2012,997,Semi-Annual PM,PM Filter Fan motor bearing and belt,40045;45858,PM,RS,PM,FALSE

5,9,2012,963;422;740,Too hot, CHW valve,60952,Adjust,MJ,Temperature,FALSE

```
//Structure of the csv files for inputs of space information
```
space ID, occupants number, usage type, number of heat-generating equipment, space access restriction, personnel who has access

```
//Examples of rows in the csv file for inputs of space information
```
A13,10,Lab,3 projectors 3 computers,TRUE,MK

A15,15,Cluster,1 printer 8 computers,FALSE,Null

A17,10,Conference,N/A,FALSE,Null