Challenges in Interpreting the Design Intent from HVAC Sequence of Operations to Assess the System Behavior: A case study

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ABSTRACT

Design, construction and operation of building heating, ventilation and air conditioning (HVAC) systems are complicated processes that generally involve several stakeholders, such as mechanical designers, control system integrators, commissioning agents and facilities managers. It is important for all these stakeholders at various phases of the project to have a thorough understanding of the system components as well as the control strategy according to the design intent of the mechanical designers. For example, when assessing the behavior of a HVAC system during operation phase, it is important for facilities managers to check for the correctness of every component's behavior and its control logic against the design specifications. The control sequences and logic of HVAC systems are primarily conveyed through schematic diagrams and textual descriptions called "sequence of operations" (SOOs) in construction documents (ASHRAE, 2004). Several challenges are associated with extracting and interpreting the information contained in these SOOs. Through a detailed analysis of a case-study conducted in relation to the information provided in the SOOs for the air handling unit (AHU) in a building, the research described in this paper highlights these challenges. Challenges such as missing information for controlled parameters as well as textual descriptions that are open to interpretations are common and result in inaccurate interpretation of the system behavior. This may adversely affect the overall performance of systems and lead to energy inefficiencies.

INTRODUCTION

HVAC systems are a very important part of most facilities not only because they help keep the occupants comfortable, but also because they use the most amount (up to 50% in commercial buildings) of energy (Perez et.al, 2008). Many construction projects adopt Building Information Modeling (BIM) technologies to enable information exchange between various teams, and yet within the current practice, information related to control sequences and strategies in HVAC systems is still being transferred through controlled systems submittals (Schein, 2007). These submittals are used by a system controls integrator to interpret and implement the HVAC controls into building automation systems (BAS) (Schein, 2007).

"Sequence of Operations" (SOOs) is a textual narrative that is a part of the control submittal in the final construction documents. The SOOs are written for each system schematic diagram describing the expected behavior of all components in all their operation modes. They provide a way to convey the designer's intent for controlling the system (Baumann, 2004). Various system related information, such as operation schedules, set points for parameters, and control dependencies that cannot be represented in the schematics are conveyed through SOOs. The narratives in SOOs are often accompanied by graphs, tables, and formulas that may assist in understanding the SOOs (ASHRAE, 2004). Through a case study, this paper delves into the specifics of interpreting these SOOs for an AHU. Further, the challenges posed by the present approach to interpret these SOOs are analyzed.

CURRENT PRACTICE

State of the art approaches associated with defining SOOs. The SOOs conveying the as-designed control strategy of the system are generated by the mechanical designers and are eventually used by various stakeholders in a HVAC lifecycle.(Keister, 2009) Misinterpretation of SOOs during the controls implementation might result in flawed controls. Inaccurate interpretation of the same SOOs in operations and maintenance (O&M) phase prevents effective diagnosis of control glitches that affect the building's energy performance. ASHRAE guideline 13-2004 specifies the SOOs along with a reference schematic diagram as one of the requirements for controls submittals. It recommends two approaches to specify direct digital controls (DDC) for HVAC control applications. (ASHRAE, 2004).

SOOs structured by operation mode: The SOOs that are structured based on the system operation mode contain narratives where each major paragraph describes one operating mode that the system is designed for, such as the occupied mode or the unoccupied mode (ASHRAE, 2004). This approach is useful to explain the control strategies for each mode and emphasizes on the changes that are required for the system to switch from one mode to another. The following is an example: ***"****Occupied mode: Pumps P-1 and P-2 shall start, current switch will indicate status."*

SOOs structured by HVAC system components: The SOOs structured by HVAC system components contain major paragraphs that describe a single component (such

as valves, dampers, pumps, etc.) or its property (such as temperature control, pressure control, etc.) in all operation modes (ASHRAE, 2004). It is easier to understand the behavior of a single component in all its operation modes in this approach. The following is an example:
"Pump start/stop: On a call from one of the units, pump P7 shall start"

The guideline defines approaches to structure the information in SOOs. However, it does not explicitly define what information items should be included in the SOOs to enable its clear interpretation. Hence, current guidelines are limited in terms of guiding design engineers to define SOOs that are unambiguous and that can provide complete information for all the controlled parameters, components and operation modes of a given HVAC system.

Relevant studies mention the vagueness of language used in SOOs in the current practice (e.g., Schein, 2007; Keister, 2009). They either focused on approaches to improve flow of logic in SOOs, such as using a graphical approach to present the SOOs (Keister, 2009), information modeling to BAS and its relation to SOOs (Schein, 2007). This analysis suggests the need for a formal representation of the SOOs to prevent energy wastage due to mis-implementation of HVAC controls.

CASE STUDY AND FINDINGS

Context and description of the study. A LEED platinum certified six story office building that was built in 2012 and occupied in 2013 was used for the case analysis. The project was chosen for the study as the information related to all project phases was available for analysis (ASHRAE, 2007). The SOOs related to the AHU used to condition the restrooms, tea-kitchens, IT rooms, mechanical rooms and conference rooms in the building are analyzed in this paper. Figure 1 shows a schematic of the AHU.

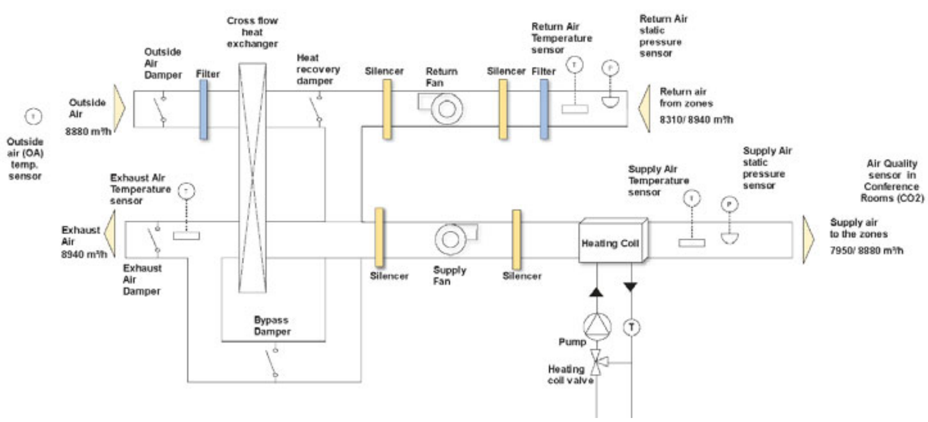

Figure 1. AHU schematic diagram from the mechanical designer

Understanding the SOOs and the system schematics. We analyzed the SOOs for the AHU and performed expert elicitation with the engineers involved in the project to identify the information items that would be required to interpret the system functioning (Gilligan, 1997). These identified information items for the AHU are presented in Table 1, first column. It is required that an SOO should precisely describe each information item in all its operation modes. The second column in Table 1 describes if the information item is the controlling parameter or if it is being controlled by other parameters according to the description. The SOOs for this AHU were structured based on the component properties like temperature, pressure, air quality etc., that correspond to the second approach to narrate the SOOs that was described earlier. The complete narratives of the five control sequences for the AHU are listed in column 3 of Table 1. These narratives were associated with the schematic diagram given in Figure 1. The exhaust air temperature control sequence used an additional graph, as given in Figure 2, to describe the dependency of exhaust air temperature and outside air temperature.

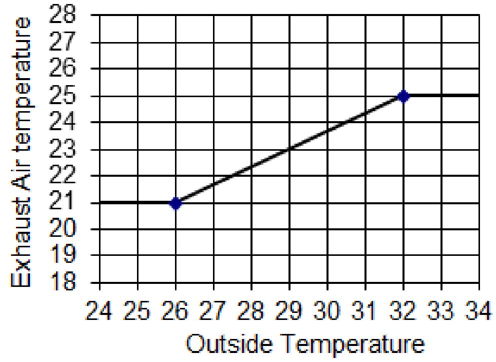

Figure 2 Exhaust air temperature control graph

Table 1 provides a detailed analysis of the SOOs for the AHU that was used to interpret the SOOs. Using the SOOs, detailed schematics were generated by the authors for all the operation modes and the status of each component was assessed based on the narratives in the SOOs. While developing these detailed schematics, missing information items, as well as the narratives that could not precisely define the set point values / control logic were identified. The third column contains the actual narratives from the SOOs for the AHU. The highlighted text in this column corresponds to the parameters that could not be precisely interpreted. The last column refers to the highlighted text in column 3 and lists the issues identified or any comments for the information items that could not be interpreted.

Challenges associated with interpretation of SOOs

The challenges that were identified in this study can have a significant impact on the interpretation of SOOs. The same challenges were identified at varying levels in the other 10 cases that we analyzed highlighting the recurrence of these issues. These challenges can be categorized into five broad categories:

Table 1. Analysis of the information items for the AHU SOOs

Information Item	Function	SOO Narrative (Excerpts from the Controls submittal)	Issue/ Comment
I. Exhaust air temperature control sequence			
Outside air temperature	Controlling parameter	The PI master controller decides the slave controller based on the deviation from the set point of the exhaust air temperature The desired base value is 21 degrees C. The slave controller controls the supply air temperature[1]. The exhaust temperature controller puts, on the basis of its deviation, the regulated units in the following sequence: Bypass damper - recirculation flap – preheater[2] The desired value of the master controller is raised depending on outdoor temperature over the summer compensation (Fig. 2)	
Supply air temperature	Controlled parameter		Missing set point, [1]Control logic not defined.
Heat recovery damper position	Controlled parameter		Missing set point, [2]The control logic of sequence not defined.
Bypass damper position	Controlled parameter		Missing set point, [2]The control logic of sequence not defined.
Exhaust air temperature	Controlled parameter		
II. Supply air pressure control sequence			
Supply Fan status	Controlling parameter	The supply pressure regulator puts the components in following sequence based on its deviation: Supply fan- The controller will be released after completion of the start off. The desired base value of the controller amounts to 290 Pascal. The desired base value is determined based on the required or measured air flow and the pressure that corresponds to it. Supply fans and Return fans: In automatic mode, the fan runs at the respective rotational speed predetermined by the controller.[1]	Missing set point, [1]The variable frequency drive (VFD) control logic for supply fan is not described.
Supply air pressure	Controlled parameter		
III. Return air pressure control sequence			
Return Fan status	Controlling parameter	The return air pressure regulator puts the components in the following sequence: Return fans - The controller will be released after completion of the start off. The desired base value of the controller amounts to 300 Pascal. The desired base value is determined based on the required or measured air flow and the associated pressure there. Supply fans and Return fans: In automatic mode, the fan runs at the respective rotational speed predetermined by the controller.[1]	Missing set point, [1]The VFD control logic for return fan is not described.
Return air pressure	Controlled parameter		
IV. Min. limitation of the return temp. of the pre-heater control sequence			
Hot water supply valve status	Missing	The return temperature of the heating coil is controlled to a minimum temperature set point. When the system is not functioning, the controller has direct	Missing set point, [1]Control logic through direct access not defined.

Hot water return temperature	Controlling parameter	access to the Heating coil valve.[1] During the operation of the system, a maximum value is selected from the control values of the heating coil return water temperature controller and the supply air temperature controller. The larger signal is fed to the heat recovery damper. The desired base set point of the controller is 20 degrees C. The heating coil return temperature controller is released when the system is non-functional.[2] *Bypass damper heat recovery* If the freeze protection of the heat recovery signals, the bypass valve of the heat recovery is ascended.[3]	Missing set point, [2]Control logic upon release not defined.
Supply air temperature	Controlling parameter		Missing set point
Heat recovery damper position	Controlled parameter		Missing set point
By-pass damper position	Controlled parameter		Missing set point, [3]Control logic of bypass valve not defined clearly
V. Indoor air quality control sequence			
CO2 level set point	Controlling parameter	Indoor air quality control sets, based on its deviation, the regulated units in the following sequence: The controller will be released after completion of the start off. The desired base value of the controller amounts to 550 ppm.	Missing controlled parameter (i.e., the component to be controlled to maintain the set point not mentioned)
VI. Plant switch command control sequence			
Outside air damper position	Controlling parameter	After the plant switch command is turned on, the first thing to occur is that the shutoff dampers are activated. [1] After an off-response from the dampers has occurred, the exhaust fans and air supply are released. After an ON – response from the remaining two fan controllers, the associated actuators for the control operation are released. The plant switch command is controlled by a time schedule.	Missing set point and time schedule, [1] The controlling parameters (shutoff dampers) not clearly defined.
Exhaust air damper position	Controlling parameter		Missing set point and time schedule, [1] The controlling parameters (shutoff dampers) not clearly defined.
Supply air fan status	Controlled parameter		
VII. Information items from the Schematic drawings that are missing in the SOO narratives (Refer to Fig. 1)			
Outside air flow rate, Supply air flow rate, Return air flow rate, Exhaust air flow rate			
VIII. Other missing information items in the SOO narratives			
Return air temperature, Hot water pump status			

i. Narratives within which the set point values / reset schedules were not explicitly stated. 50% of the information items had this issue in this case study. The fourth column in Table 1 identifies all these instances.

ii. Narratives that do not describe the controlling action being performed. The highlighted text in column 3 in Table 1 defines the controlled or controlling parameters but not the logic. For example, in the fourth control sequence:

"The return temperature of the heating coil is controlled to a minimum temperature set point. When the system is not functioning, the controller has direct access to the Heating coil valve."

This narrative defines the component being controlled as the heating coil valve and the controller as the minimum temperature set point but does not define the controlling action. Such issue was found in 33% of the information items.

iii. Information items that had to be acquired from multiple sources and are not adequately narrated in the SOOs. For example, the air flow rates for the AHU were acquired from the system schematic but the state of the system when these air flows apply are not adequately narrated in the SOOs. 17% of the information items had this issue.

iv. Narratives that do not define the controlled/ controlling parameter of certain information items in the dependency logic. This corresponds to the information presented in the 2nd column of Table1. For example, the narrative for the air quality control sequence describes the CO_2 level sensor reading as the controlling parameter, but does not clearly describe which component in the system is being controlled to maintain the air quality. This issue was identified for 13% of the information items listed in Table 1.

v. Missing information items in the SOOs. The last row in Table 1 lists the critical information items required to assess the state of the system at various modes that are missing in the SOOs. 8% of the information items were missing in the study.

All five categories of the identified challenges contribute to misinterpretations of SOOs leading to various problems in the HVAC lifecycle. Hence, all five categories should be kept in mind while developing approaches to formally represent SOOs with complete requirements that are not open to misinterpretations.

CONCLUSION

Main challenges faced by various stakeholders in the interpretation of the system functioning from SOOs were identified through a detailed case study. These challenges include missing information items, missing set points, or insufficient descriptions. The research in this paper points to the inadequacies in narrating SOOs used presently to communicate the design intent of HVAC systems. There is a need for the information items in SOOs to be formally defined with a granularity and in a manner that is not open for interpretation by various parties to minimize anomalies in system performances and energy use (Wang et.al, 2011). Future work in this research would involve a study to develop formal approaches that can enable design engineers narrate SOOs with information required by all parties with no ambiguities.

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