Towards a Formal Approach for Determining Functions of HVAC Components Represented in IFC

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ABSTRACT

The maintenance of Heating Ventilation and Air Conditioning (HVAC) systems is one of the fundamental activities in facilities management groups. HVAC systems are configured from basic types of components, such as dampers, fans, valves and coils, and there are usually multiple instances of the same type of components performing different functions in an HVAC system. For example, in relation to dampers, an HVAC system can contain an outside air damper, a discharge air damper, a return air damper, a mixed air damper, and multiple variable air volume dampers. It is also a similar case for other components such as valves, coils and fans. When HVAC mechanics perform maintenance activities, they usually need to check HVAC components with specific functions, and know information about such components, such as "where is the outside air damper?" The information related with different HVAC components can be represented and exchanged using Building Information Models (BIM). Among BIM data standards, IFC represents more information in relation to HVAC for Facilities Management (FM) purpose. However, the bottleneck of using IFC to provide information support for HVAC maintenance is that current IFC standard does not differentiate functions of HVAC components of the same type, and thus it is not possible to identify HVAC components with specific functions and retrieve their information from an IFC file directly. This study presents the need for an approach to deduce the functionalities of HVAC components from their existing topological information represented in IFC files. This approach, once formalized, can be used as a basis to automatically retrieve required information from IFC-based BIM for HVAC mechanics during maintenance tasks.

INTRODUCTION

Sound operation of HVAC systems ensures people's productivity and health by providing comfortable indoor environment (Seppänen and Fisk 2006). When there are problems with indoor comfort, HVAC mechanics need to investigate HVAC systems and spaces to identify and correct the sources of problems. The troubleshooting of HVAC related problems is well recognized as a challenging task because of the increased complexity of modern HVAC systems and the lack of apparent causes when problems occur (Burton 1993; Budaiwi 2007). It is also a known fact that HVAC mechanics need different information items when responding to different work orders but the required information is not readily available (Yang and Ergan 2013).

Storing the required information for troubleshooting HVAC related problems in Building Information Models (BIM) and retrieving information from BIM can provide HVAC mechanics a more efficient way to get access to required information. Industry Foundation Classes (IFC), Green Building XML (gbXML), EnergyPlus Input Data Dictionary (IDD) and HVAC information exchange (HVACie) are the major data standards to represent HVAC related information. While gbXML, EnergyPlus IDD and current HVACie focus on representing HVAC information at the design stage, IFC aims to cover building lifecycle information for different disciplines and it contains rich information for HVAC systems and their components which can be used to access and exchange information for HVAC maintenance activities. However, a challenge of using IFC to retrieve required information to support HVAC maintenance is related to the limitation of IFC in differentiating functions of HVAC components of the same type. In an HVAC system, various components of the same type exist with different roles, and HVAC mechanics usually need to check the instances in a system and know their information during troubleshooting. Using current IFC representation, however, it is not possible to identify instances of HVAC components with specific functions and retrieve their information from an IFC file directly.

This paper uses work order examples to show the challenge of using IFC to exchange HVAC related information during the FM phase to support HVAC maintenance activities and the need for an approach to determine the functionalities of HVAC components represented in IFC. This paper also reviews basic types of HVAC systems, and summarizes the common HVAC components that usually have multiple instances in one HVAC system performing different functions. An approach of using topological information represented in IFC to deduce specific functions of HVAC components is proposed, and the feasibility of such an approach is demonstrated by using different damper types as examples.

MOTIVATING CASE STUDY

The authors have conducted a case study with a Facilities Management Services group in a campus about the current practice of troubleshooting HVAC related problems. The initial stage of the case study includes shadowing of HVAC mechanics on 23 work orders issued for HVAC related problems. Table 1 shows two work order examples, the actions taken by HVAC mechanics, the HVAC components that were checked, and the associated required information. The table shows that different components were checked by the HVAC mechanics when they worked on different work orders, which necessitated knowing different sets of information. All the work orders recorded during shadowing showed similar patterns.

In the current practice, HVAC mechanics have to manually collect this required information through field tracing and inspection, or refer to different data sources, which will result in time waste to search and access to the information (Yang and Ergan 2013). Storing the required information in BIM and retrieving information from BIM can provide HVAC mechanics a more efficient way to get access to the required information. IFC data model contains rich information for HVAC systems and their components which can be used to access and exchange information for HVAC maintenance activities. However, a challenge of using IFC is to find the HVAC components in the data model that are corresponding to the ones that mechanics want to check when they work on a specific work order.

Table 1. Work order examples

Actions performed by HVAC mechanics	Components and information checked
Work order 1: Office is too cold	
(1) Checked the thermostat; the current temperature reading was 62 °F while the setpoint was 72 °F (2) Opened a set of ceiling tiles; checked if the thermostat controlled the reheat valve properly; found that the hot water pipes were not connected to the reheat coil (3) Logged in the BAS; checked the VAV damper setpoint (4) Adjusted the VAV damper airflow setpoints (min/max) under heating mode to 0 (5) Reported a new work order to get the reheat coil properly connected	Thermostat: location, current temperature reading, temperature setpoint Reheat valve: location, control relationship with thermostat Reheat coil: location, connection relationship with hot water system VAV damper: airflow setpoint
Work order 2: Odor in the room	
(1) Opened a set of ceiling tiles; found the Air Handling Unit (AHU) (2) Checked the filter in AHU; it was clean (3) Traced the ductwork; found the location of the Outside Air (OA) intake; investigated the area where the outside air came in to find the source of the odor (4) Traced the ductwork to find the OA damper; found that the damper was stuck at closed position (5) Fixed the damper	Filter in AHU: location, filter status OA intake: location OA damper: location, damper operation status

HVAC systems are configured from basic types of components, such as dampers, fans, valves and coils, and there are usually multiple instances of the same type of component, performing different functions, in an HVAC system. For example, in relation to dampers, an HVAC system can contain an outside air (OA) damper, a discharge air (DA) damper, a return air (RA) damper, a mixed air (MA) damper, and multiple variable air volume (VAV) dampers, with different roles in the system. When HVAC mechanics work on different work orders, they need to check components with different functions. For instance, the two work order examples in Table 1 show that HVAC mechanics checked dampers with different functions in these two cases: VAV damper, and OA damper, respectively. Within IFC however, all instances of dampers are represented using IfcDamper class. In such a case, it is not possible to identify instances of VAV damper or OA damper and retrieve their information from an IFC file directly. It is also a similar case for other components such as valves, coils and fans. Therefore, there is a need for an approach to determine functions of HVAC components represented in IFC.

BACKGROUND RESEARCH

While BIM has been widely adopted in design and construction, application of BIM to support FM activities is still in its early stages. Previous research studies that focus on BIM for FM include developing IFC-compatible data models for FM purposes (Wix et al. 1999; Hassanain et al. 2001), storing and visualizing changes of facilities caused by maintenance and repair work in BIM (Akcamete et al. 2011), and using different computerized approaches to leverage BIM to provide information support for maintenance work, such as case-based reasoning (Motawa and Almarshad 2013), augmented reality with makers (Lee and Akin 2001), and fault tree analysis (Lucas et al. 2012). In addition to these, various information models that were developed for HVAC systems include embedded commissioning models for building commissioning process (Turkaslan-Bulbul and Akin 2006), models to represent building automation systems (Schein 2007), and functional taxonomy of HVAC components (Liu et al. 2011). Though these studies provide points of departure while identifying requirements of HVAC mechanics for troubleshooting, no previous studies focused on identifying the subtypes of a major component within a system.

As the most widely used building information exchange standard, IFC has a recent release IFC2x4 (IFC4) (Building Smart Alliance 2013). In IFC4, HVAC related representation is covered in HVAC and Building Controls domains. In the HVAC domain, common HVAC components have their corresponding IFC entities, such as IfcAirTerminal, IfcCoil, IfcDamper, IfcValve, IfcFilter, and IfcFan, and Building Controls domain enables representation of basic components in a control loop, including sensors (IfcSensor), controllers (IfcController) and actuators (IfcActuator). These IFC entities have properties such as location, size, manufacturer, warranty, operational statuses, setpoints, mean time between failures, etc., which are among the various information items needed to support HVAC maintenance activities. However, even though IFC4 has enumeration entities to represent subtypes of these components based on different ways how they work (e.g., dampers that used as balance damper, fire damper, control damper, etc.), it is not detailed enough to differentiate various HVAC components of the same type with different functions (e.g., dampers that work as VAV dampers, OA dampers or RA dampers).

Besides IFC, other major data models related with HVAC include gbXML, EnergyPlus IDD, and HVACie. gbXML was developed to transfer data from BIM to building performance analysis tools, EnergyPlus is a tool developed by U.S. Department of Energy to perform building energy simulation and IDD defines the required data specifications, and HVACie is under development to define information exchange specifications of HVAC systems as an extension of IFC's Model View Definition (MVD) (Hitchcock and East 2012). Currently HVACie describes HVAC design process and document data exchange requirements relevant to HVAC design phase, while gbXML and EnergyPlus IDD focus more on represent building elements and HVAC systems from the perspective of energy-related properties, such as equipment schedules, capacities, and efficiencies. These models lack the entities to represent the required information for HVAC maintenance in FM phase, such as operational statuses and mean time between failures, which on the contrary, are included in IFC.

RESEACH METHOD AND FINDINGS

The authors first reviewed the different types of HVAC systems, identified the common HVAC components that have different functions, and presented an approach to determine the functions of HVAC components represented in IFC. The findings are presented below:

(1) Basic types of HVAC systems and the focus of this study. An entire HVAC system is composed of two sub-systems: a primary system and a secondary system (ASHRAE 2000). Primary system produces cooling or heating sources, such as chilled water and hot water, and secondary system uses the heating/cooling sources to condition spaces. Primary system is usually located remotely from the buildings they serve. On the contrary, secondary systems are usually located in buildings that they serve. These two sub-systems are highly independent (ASHRAE 2000) and the focus of this research is on the secondary systems (referred as HVAC systems in this paper).

Secondary HVAC systems have four basic categories (McDowall 2007): 1) All-air systems, which only use air as medium to condition spaces. All-air systems have many variations and ASHRAE classifies them into 15 categories (ASHRAE 2000); 2) Air-and-water systems, which use both air and water to condition spaces; 3) All-water systems, which only use water to condition spaces, and 4) Unitary, refrigeration-based systems, which use local refrigeration equipment to produce air conditioning, such as window air-conditioner. Since unitary systems have much simpler configuration, they are not within the scope of this study.

(2) Basic types of HVAC components and their subtypes. Though different types of HVAC systems perform different mechanical and thermodynamic procedures, they are composed of basic types of HVAC components. The common HVAC components include: dampers, coils, fans, valves, filters, (de)humidifiers, diffusers, ducts, pipes, and pumps. Based on studying various configurations of a wide range of HVAC systems detailed by ASHRAE (as explained in the previous section), it was found that HVAC components that a) originate from the same type, b) have multiple instances in one HVAC system and c) perform different functions (referred as subtypes) are dampers, coils, fans, and valves. Table 2 shows the common subtypes of these components.

(3) Use information in IFC to deduce HVAC component subtypes. As discussed above, current IFC schema does not have an explicit representation to differentiate subtypes of HVAC components. However, IFC defines rich topological information that can be leveraged to deduce the functions of HVAC components. HVAC components' connectivity is represented via IfcRelConnectsPortToElement, IfcDistributionPort, and IfcRelConnectsPort entities, and IfcDistributionPort entity has a property of flow directions, e.g., SOURCE or SINK, as shown in the UML diagram in Figure 1. Thus the connectivity among HVAC components and the air or water flow directions can be known.

Table 2. Common HVAC components and their subtypes

Dampers	Coils	Valves	Fans
Outside air damper; Return air damper; Exhaust/relief air damper; Mixed air damper; Discharge air damper; Coil bypass damper; Zone bypass damper; VAV damper; Mixed box damper	Heating coil; Cooling coil; Preheat coil; Central reheat coil; Zone reheat coil	Heating coil valve; Cooling coil valve; Preheat coil valve; Central reheat coil valve; Zone reheat coil valve; Radiator valve	Supply air fan; Return air fan; Exhaust/relief air fan; VAV fan;

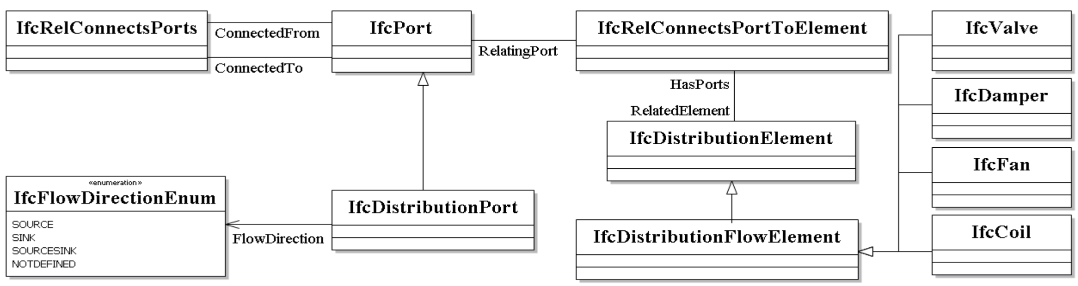

Figure 1. UML diagram of IFC4's representation of HVAC components' topological relationships (generated using IFC4 specification, Building Smart Alliance 2013)

It is observed that there are certain topological constraints that an HVAC component with a specific function follows. Figure 2 shows a schematic diagram of a typical single duct, VAV reheat type HVAC system. If we consider the damper as an example, the outside air damper directly connects to outside without going through the other dampers and appears in the supply air flow direction and in the central air handling unit (AHU), as shown in Figure 2. However, the VAV damper directly connects to a conditioned space without going through other dampers, and also appears in the supply air flow direction but in a local system.

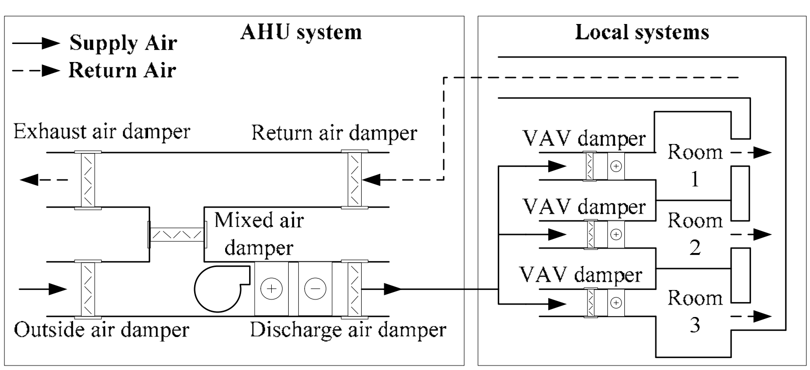

Figure 2. Schematic diagram of a typical single duct, VAV reheat HVAC system.

We have identified similar constraints for various other damper subtypes and Table 3 summarizes the findings. These constraints are always followed by these damper subtypes no matter how different the system configurations are. Such topological constraints can be deduced by reasoning with an IFC file for a given HVAC system and the spaces they serve via IfcRelContainedInSpatialStructure, IfcDistributionPort, IfcRelConnectsPort, IfcRelConnectsPortToElement, and IfcFlowDirectionEnum. Each different subtype then can be differentiated by checking their topological constraints.

Table 3. Constraints of topological relationships for different damper subtypes

Damper subtypes	**Topological hierarchy**	**Topological relationships with spaces or other components**	**Air flow direction**
Outside air damper	AHU system	Directly connects to outside	Supply air direction
Return air damper	AHU system	Directly connects to served space	Return/exhaust air direction
Exhaust/relief air damper	AHU system	Directly connects to outside	Return/exhaust air direction
Mixed air damper	AHU system	N/A	Return/exhaust air direction
Discharge air damper	AHU system	Appear after heating/cooling coils	Supply air direction
Coil bypass damper	AHU system	Appear after outside air damper and before heating/cooling coils	Supply air direction
Zone bypass damper, VAV damper, Mixed box damper*	Local system	Directly connects to served space	Supply air direction

*Note: these three damper subtypes do not need differentiation since they belong to different types of HVAC systems and thus cannot appear at the same time in an HVAC system

This paper uses dampers and their various subtypes to demonstrate the feasibility of using the topological relationships in IFC to deduce functions of HVAC components of the same type. We have implemented a proof-of-concept prototype and it could successfully identify the subtypes of dampers in a given system. In future research, the topological constraints for other components, such as coils, valves and fans (as shown in Table 2), will be developed, and algorithms will be implemented to reason with IFC files to automatically retrieve information values.

CONCLUSION

This paper shows an important challenge when using IFC to exchange HVAC related information to support HVAC maintenance activities. Current IFC representation does not differentiate HVAC components of the same type with different functions (hence subtypes). By studying the configurations of different types of HVAC systems, the common HVAC components that usually have multiple instances in one HVAC system performing different functions are summarized. It was identified that various components such as dampers, coils, valves, and fans, have this issue if they were to be identified for their subtypes. It was observed from studying a wide range of HVAC configurations defined in ASHRAE that there are certain topological constraints that an HVAC component with a specific function follows, and these constraints can be obtained by reasoning with IFC's representation. The feasibility of such an approach is demonstrated by analyzing the topological constraints for dampers with different functions. In future research, the topological constraints for other components, such as coils, valves and fans, will be developed, and algorithms will be implemented to reason with IFC files to automatically retrieve information values. Moreover, the generality of the approach will be tested by using IFC files for different types of HVAC systems in different facilities.

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