REQUIREMENTS AND DEVELOPMENT OF A COMPUTERIZED APPROACH FOR ANALYZING FUNCTIONAL RELATIONSHIPS AMONG HVAC COMPONENTS USING BUILDING INFORMATION MODELS

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ABSTRACT

Heating, ventilating and air conditioning (HVAC) systems account for about 40% of the energy consumed in buildings. They directly control the indoor air quality and determine occupant comfort. Therefore, correct operation of HVAC systems is critical for ensuring the normal functions of the buildings. Due to the continued increase in their complexity, manual operation and maintenance of the HVAC systems has become more and more difficult. Computerized approaches, such as Fault detection and diagnosis and automated commissioning approaches, have been proposed to automate this process. These approaches use data from the HVAC systems and building context and provide information about the performance of the systems to the operator. However, the existing information standards, such as Industry Foundation Classes (IFC) and AEX cfiXML, mainly represent the geometric information and categories of the HVAC components. One important type of information that is missing is the functional relationships of the HVAC components. Functional relationships represent how different HVAC components work together to serve the functions of the system. For example, a sensor that monitors the temperature of a space is functionally related to the Variable Air Volume (VAV) box that controls the temperature of the same space. Therefore, functional relationships are needed by the HVAC system operator to reason about and adjust their configuration. The objective of the presented work is to develop a computerized approach that can automatically analyse the functional relationships of HVAC components using the available information from the existing Building Information Models (BIM). This includes the exploration of needed functional relationships of HVAC components, the classifications of functionalities of HVAC equipment and components, the development of a functional taxonomy of HVAC components, and the implementation of a prototype system for analysing the functional relationships. The primary result of the presented work is the development of an extensible computerized approach that can automatically reason about the functional relationships of typical HVAC components using information from BIM.

Keywords: Information Models Analysis, Building Information Modeling, Functional Information, HVAC Systems Modeling.

1. INTRODUCTION

Heating, ventilating and air conditioning (HVAC) systems directly control the indoor air quality and determine occupant comfort. They consume approximately 16% of the energy used in the U.S. (DoE 2008; EIA 2008). Faults in HVAC systems, such as malfunctioning sensors and controllers, improper execution of control logic and sub-optimal control algorithms, can reduce occupant comfort and/or result in energy waste. Previous research showed that 25 to 40% of energy used by the HVAC systems can be saved by mitigating faults (Mansson and McIntyre 1997; Liddament 1999; Liu et al. 2002;

Roth et al. 2005). Therefore, the correct operation of HVAC systems is critical for achieving energy efficient buildings.

The increasing requirements for better indoor air quality control have resulted in HVAC systems becoming more and more complex and it is very difficult, if not impossible, for system operator to manually monitor and analyze the performance of hundreds of components in the system. Therefore, computer applications have become more and more important in automating the management of these systems (Lee et al. 2004; Katipamula and Brambley 2005; Jagpal 2006).

Information models for HVAC systems are needed by the computerized approaches to reason about the properties of the components and exchange information among different applications. However, the existing information standards, such as Industry Foundation Classes (IFC) (buildingSMART 2010), AEX cfiXML (FIATECH 2011) and ISO 15926 (Leal 2005), mainly represent the geometric information and categories of the HVAC components. One important type of information that is missing is the functional relationships of the HVAC components. Functional relationships represent how HVAC components work together to serve the functions of the system. For example, in a Variable Air Volume (VAV) box-based HVAC system, a sensor that monitors the temperature of a space and a damper that controls the amount of air provided to the space are functionally related to the VAV box that controls the temperature of the same space. Therefore, functional relationships are needed by the computerized approaches to interpret the configuration of the HVAC control systems and analyze their performance.

The objective of the work presented in this paper is to develop a computerized approach that can analyze the functional information of HVAC components using the available information from the existing Building Information Models (BIM). The discussion starts with a motivating case study on the need for a computerized approach for generating functional relationships of HVAC components automatically. Then, this research classifies the functions of HVAC equipment and components and identifies the patterns that are used by humans to interpret the functional relationships of HVAC components. An extensible functional taxonomy is developed to support the information requirements for analyzing the functional relationships. Finally, the proposed approach was tested using a prototype and the feasibility of the proposed approach was verified.

2. PROBLEM STATEMENT

To analyze the requirements for functional relationships of HVAC components, we studied a motivating scenario from HVAC systems operation and maintenance tasks.

Motivating scenario: Diagnosing HVAC systems for a hot call reported by an occupant.

Hot/cold calls are typical facilities management (FM) service requests that are relevant to the performance of HVAC systems. They are reported by occupants who find that the temperature of their space is higher/lower than their expectation (Turner et al. 2001; Claridge et al. 2003). Space temperature control is one of the primary functions of HVAC systems (ASHRAE 2009). In a typical HVAC system, there are several components, such as an air handling unit (AHU), a supply fan, a damper in the air diffuser and a thermostat, which can affect the space temperature. Therefore, a system operator needs to check the working status of all these components to diagnose the cause of the call.

Figure 1 shows the flow chart of part of a diagnosis process for a hot call service request with a HVAC system using Variable Air Volume (VAV) box.

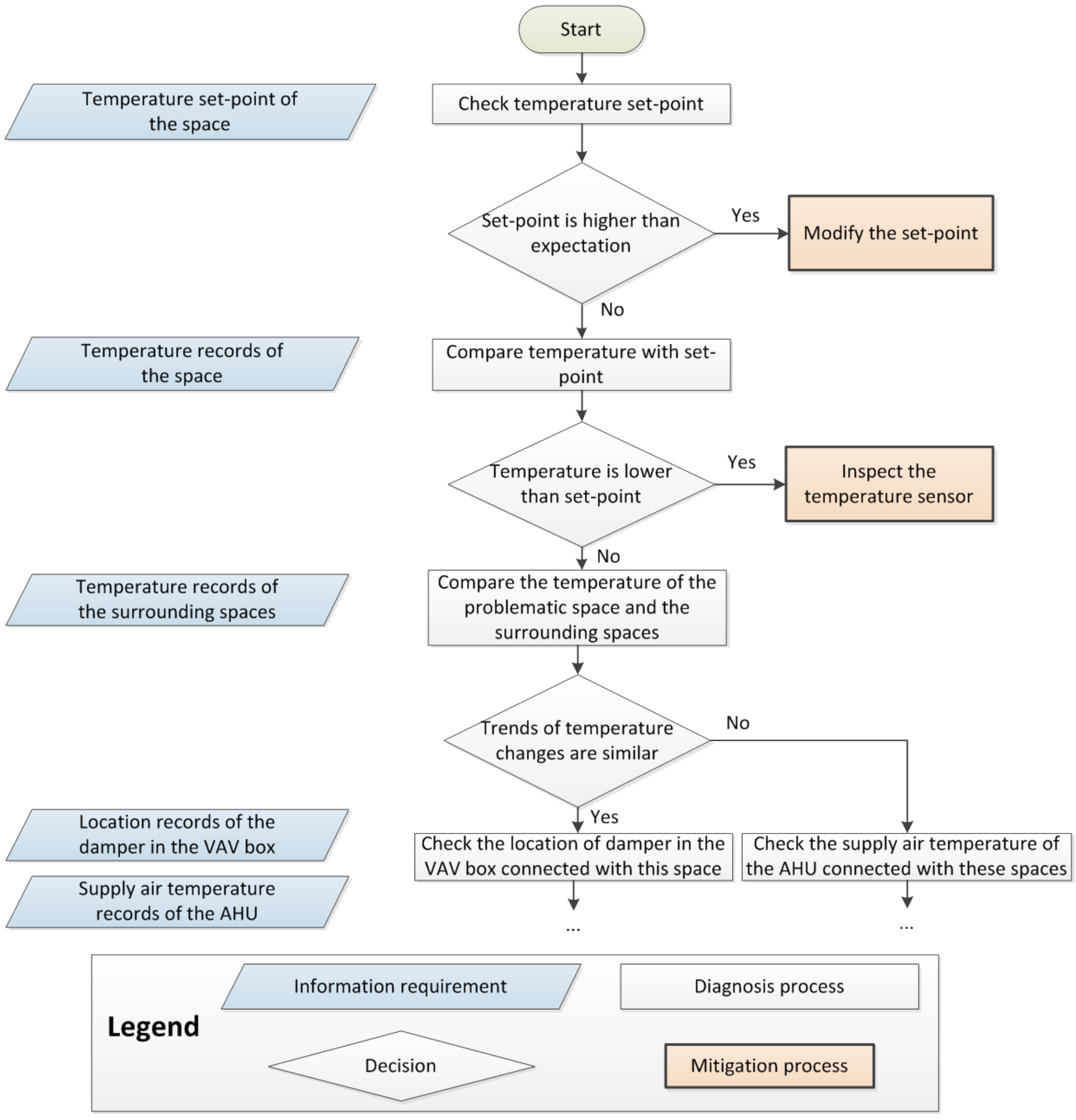

Figure 1. Flow chart for the diagnosis process of a hot call service request

As depicted in Figure 1, to diagnose the cause of the hot call, the system operator first checks whether the occupants have set a high value for the temperature set point of the space by mistake. The records of temperature set point are checked and if it is the cause of the hot call, the system operator will solve this problem by modifying the set point. Otherwise, the problem may be caused by a fault associated with the temperature sensor in the space. For example, if the measurements of the temperature sensor drift by -4°F, the HVAC systems will try to maintain the temperature of the space at 4°F higher than the set point. The system operator will compare the temperature records with the set point values to determine whether the temperature sensor is working correctly or not. If the temperature records always drift from the set point by a certain value, the system operator will inspect the temperature sensor. If the temperature sensor is working correctly, the system operator needs to continue to diagnose the other components. One way to determine whether the fault is associated with the local VAV box control or the AHU that serves multiple spaces is to check whether the other spaces that are controlled by the same AHU have similar problems or not. The system operator will retrieve the temperature records of the spaces that surround this space and check whether these spaces have similar problems. If they do, the system operator will then further diagnose the components in the associated AHU. For example, the system operator will check the supply air temperature to determine whether the AHU is able to provide the required cooling loads. If only this space behaves problematically, the system operator will check the working condition of the VAV box. For instance, if the damper in the VAV box is stuck, the space will not be provided with enough cooling air. The system operator will check the records of the damper location to determine whether the damper has been working correctly or not.

The diagnosis process shown in Figure 1 illustrates that in order to diagnose the working condition of HVAC systems, system operators need to identify the HVAC components that are relevant to the problem. In the case of diagnosing the cause for a hot call, the system operator needs to identify the components that impact the air temperature control. During the design and installation of the HVAC systems, engineers have created the functional relationships between the HVAC components and typically maintained them in two types of documents: mechanical plan drawings and P&ID (Piping and instrumentation diagram) drawings. Figure 2 shows examples of the drawings.

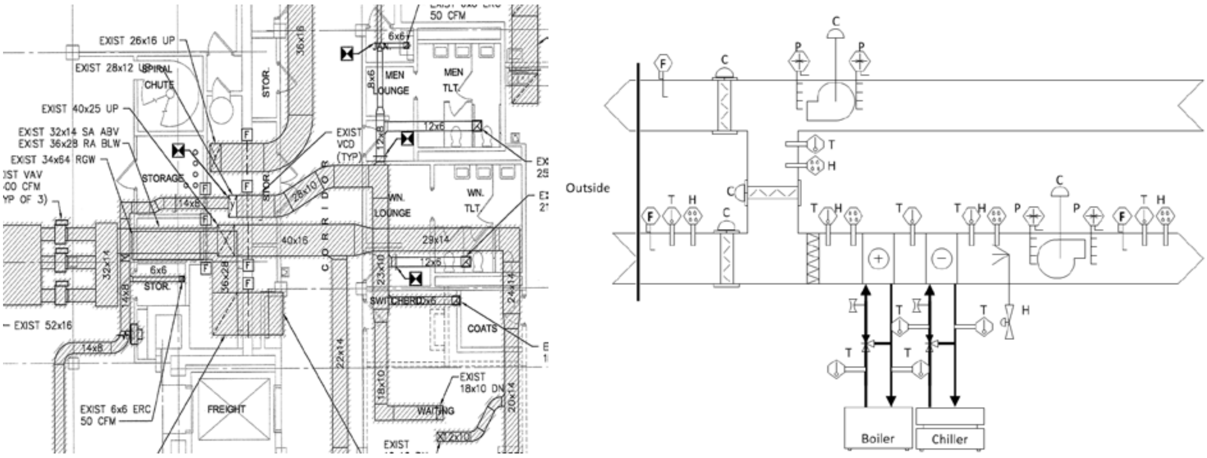

Figure 2 Examples of mechanical plan drawing (left) (a section of mechanical plan of a campus building) and P&ID drawing (right) (adopted from Sugarman (2005))

The mechanical plan drawing shows the location, geometry and connectivity of the HVAC equipment, ducts and pipes. The building elements and HVAC system components are modeled together so that their relative spatial relationships are available. However, the mechanical plan drawings typically only contain information for ducts, pipes and equipment, such as AHU and VAV boxes. They do not contain the detailed components, such as sensors, actuators and controllers. Therefore, a system operator cannot identify the individual components and their functional interrelationships from this drawing.

The P&ID drawings are schematic drawings that depict the configuration of a type of HVAC control system. The drawings show the HVAC components, such as sensors, controllers and controlled devices that compose the HVAC system. The connectivity and relative location of these components are also illustrated in this drawing. However, because the P&ID drawing shows a type of HVAC system, it does not represent the individual instances that are installed in the building. Hence, this drawing also does not allow the system operator to identify the individual components and their functional relationships.

To summarize, because the functional relationships of the HVAC components are not represented in existing HVAC design documents, it is challenging to retrieve the needed information for system diagnosis. An approach is needed to represent the functional relationships of the HVAC components and enable information query.

3. RESEARCH APPROACH

The research presented here first classifies the functions of the typical HVAC components. Then, a functional taxonomy of the components is proposed to enable the formal representation of their functions. A reasoning mechanism is developed to use the functional taxonomy and spatial relationships of HVAC components to automatically reason about the functional relationships. The reasoning mechanism was implemented in a prototype and tested with the motivating case.

3.1 Background research

Standard information models provide unified and formal ways to represent the properties and relationships of the objects in different domains of the real world. For example, Building Information Models (BIM), such as IFC, provide rich semantic information about the facilities inside a building (Eastman 2008). The ISO standard 15926 was developed to formally represent the life-cycle information of components in process plants and enable the integration of information that is created by different stakeholders (Leal 2005). Using the semantic information stored in these information models, mechanisms that are implemented using computer algorithms can be developed to process information automatically. For example, Borrmann and Rank (2010) developed an approach that answers spatial queries of the building elements by reasoning about information from a BIM (Borrmann and Rank 2010). The research presented here utilizes the standard information models that represent building context and HVAC systems configuration to reason about the functional relationships among HVAC components.

3.2 Classification of functions and controlled mediums of the typical HVAC systems

HVAC components all serve certain functions of HVAC systems. For example, the heating/cooling coil directly controls of indoor air temperature. Similarly, humidifiers and dehumidifiers affect the indoor air humidity. Hence, to specify the required functional relationships of the HVAC components, the types of control that the HVAC systems serve need to be identified first.

The primary functions of the typical HVAC system include controlling three aspects of indoor air condition: temperature, air distribution rate and humidity (ASHRAE 2009). Different designs of an HVAC system use different equipment and components to achieve these controls. According to (Gupton 2002; McDowall 2008), typical HVAC systems are categorized into four types based on the energy exchange approach:

- *All air systems*: All air conditioning processes are performed with air.
- *All water systems*: All air conditioning processes are performed with water.
- *Air & water systems*: Air conditioning processes are performed with both air and water. Typically, the primary energy exchange processes are air based. Water based energy exchange is used to adjust the local additional requirements.
- *Packaged systems*: All air conditioning processes are performed in distributed and local equipment.

These HVAC systems use two mediums, *air* and *water*, to transport and deliver the services of temperature control, sufficient air distribution and humidity control. For example, the temperature of a space is controlled by the temperature and the amount of supplied air in the all air systems, while it is affected by the temperature of the water and surface area of the radiator in the all water systems. Hence, HVAC systems are able to control the indoor air conditions by adjusting the properties of these two mediums.

Each of the individual HVAC components is related to one or several properties of the mediums that are transported or controlled by them. For example, the fan and damper in the air duct are able to affect the airflow rate and therefore, control the amount of air provided to the downstream duct. The temperature sensor located in a supply-air diffuser measures the temperature of the air supplied to the space and the controller uses this measurement to adjust the temperature of such space. *Air* and *water* are transported and affected through various types of HVAC components that work together to determine the final condition of the mediums. Therefore, HVAC components are functionally related to each other by the mediums that they measure or affect.

3.3 Classification of functions of HVAC components

According to Sugarman (2005), McDowall (2008) and ASHRAE (2009), HVAC control systems consist of four types of components: sensors, set-points, controllers and controlled devices. These components are part of different control loops in the HVAC sytems to serve different types of control. Figure 3 shows an example of a local control loop that adjusts the temperature of a space by controlling the amount of air provided to the space. Figure 3(a) shows the P&ID drawing and Figure 3(b) shows the data flows and control logic in this control loop.

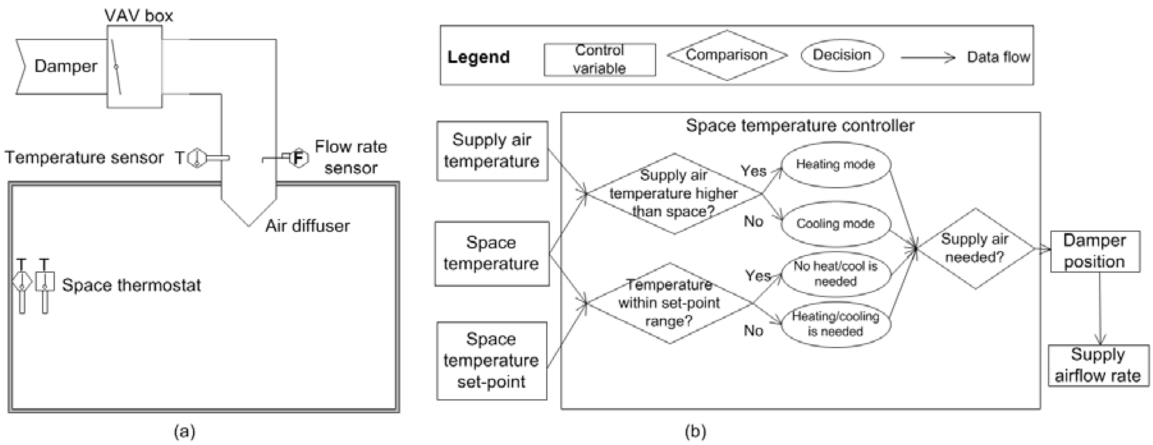

Figure 3 An example of a local control loop that adjusts the temperature of a space, where (a) shows the P&ID drawing and (b) shows the data flow in this control loop

Figure 3(b) shows the data flows among the different HVAC components and therefore, the functional relationships of these components can be interpreted from this figure. However, the diagram shown in Figure 3(b) is not represented in either the mechanical drawings or the P&ID drawings (see Figure 2 and Figure 3(a)). Currently, this diagram can be created by a human using information about HVAC components in the P&ID diagram in Figure 3(a) and knowledge of how HVAC systems work. For example, knowledge about a temperature sensor would include the understanding that such a sensor measures the surrounding environment. Therefore, if a temperature sensor is located in a supply air duct, it must measure the temperature of the supply air. Similarly, the temperature sensor located in the space thermostat is used to measure the temperature of the space. Because the air in the supply duct is transported to the air in the space through the air diffuser, it is known that air in the space is affected by the air from supply duct. Therefore, the sensors in the supply duct can be related to the sensor in the space according to their connections to the same air diffuser.

Figure 3(a) shows that there are three sensors. One temperature sensor is located in the supply air duct and measures the temperature of the air supplied to the space. Another temperature sensor is located in the space thermostat to monitor the temperature of the space. The thermostat also contains a temperature set-point input, which is used by the occupant to adjust the set-point of temperature. It is known that a damper in the air duct is able to control the airflow rate and the reheat coil in a VAV box is able to adjust the temperature of the supply air. Since this HVAC system uses a VAV box with a damper and without any reheat coil, it is known that the VAV box can only adjust the amount of air provided to the space and cannot change the supply air temperature.

A controller is installed in the VAV box that receives the three measurements and conducts three comparisons. First, it compares whether the space temperature is within the range of the set-point to determine whether heating or cooling is needed. Second, it compares the space temperature with the supply air temperature to determine whether the HVAC system is in heating mode or in cooling mode. Third, the results of the first two comparisons are used to determine how much air should be provided to the space. For example, if the space temperature is within the set-point range and the supply air temperature is lower than the space temperature, the controller will only provide minimum airflow to the space just to ensure the ventilation requirements. After determining the required amount of air, the controller adjusts the damper position to change the supply airflow rate.

This example shows that it is possible to understand the composition of the control loop in the HVAC systems using the functions of the HVAC components and spatial relationships of the components and other building elements. Therefore, if these two types of information are accessible and interpretable by a computer, it is possible to develop reasoning mechanisms to automatically analyze the functional relationships of the HVAC components. BIM can provide the spatial relationships. For example, an IFC model of a building stores the spatial information of spaces and HVAC components. However, although the type of the HVAC component is represented within several information standards, such as AEX cfiXML and ISO 15926, the knowledge of their functions is not explicitly represented. Therefore, the functions of HVAC components need to be represented in the information model to enable automated reasoning about functional relationships among the components.

Table 1 summarizes the classifications of the functions of the HVAC components. Each column in this table shows an attribute of the medium *air* or *water*. Each row shows one type of HVAC component. The mark in the cells shows the functions of the HVAC components. M means that the attribute of the medium is *measured* by the components. C means that the attribute is *controlled* by the components. S means that the attribute of the medium is the *energy supply* for this component.

Component	**Air**				**Water**	
	Temperature	**Flow rate**	**Pressure**	**Humidity**	**Temperature**	**Flow rate**
Temperature sensor	M				M	
Flow meter		M				M
Pressure sensor			M			
Humidity sensor				M		
Damper		C	C			
Fan		C	C			
Valve						C
Pump						C
Heating/cooling Coil	C				S	S
Boiler & Chiller					C	
(De)humidifier				C		
Radiator	C				S	S

Table 1 Summary of the classifications of functions of the HVAC components

With the information of functions of HVAC components and existing information models that represent the spatial information and category of HVAC components, the functional relationships among HVAC components can be automatically reasoned about and provided to system operators. The next step was to develop an approach to formally represent the functional information.

3.4 Development of a functional taxonomy of HVAC components

The development of new sensing and control technologies brings different types of components into the design of HVAC systems. Therefore, in order to generally support the reasoning of different types of components, the representation of the functional information of HVAC components needs to be developed in an extensible way. One goal of the research described in this paper is to develop an extensible taxonomy for representing this functional information. The taxonomy developed is shown in Figure 4 using a UML diagram.

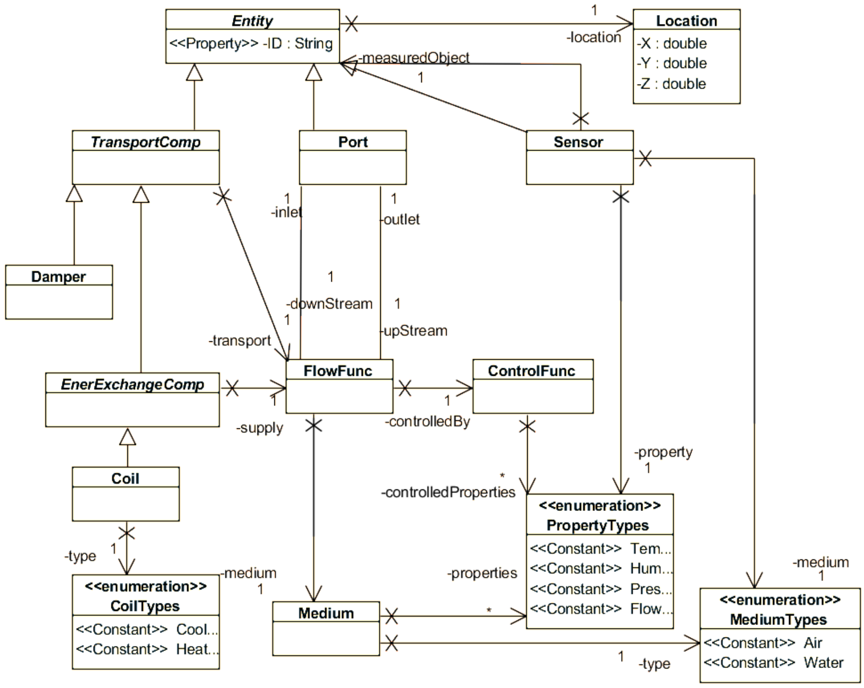

Figure 4 UML diagram of the developed taxonomy

In Figure 4, the root class of this taxonomy is *Entity* which contains the ID and location of the objects. It has three subclasses: (1) *Port*, which represents the physical connectivity of two objects and exists in the IFC schema; (2) *Sensor*, which represents all types of sensors; and (3) *TransportComp*, which represents the types of objects that can transport *air* or *water*. The *TransportComp* class has a property with type *FlowFunc* that represents the type of medium this object transports. Information about the medium is defined by the class *Medium* that has properties of the type of medium and the properties of the medium, such as temperature and pressure. If the instance of *TransportComp* can control certain properties of the medium, it has a *ControlFunc* instance as the property of *FlowFunc*. The *ControlFunc* class specifies the properties that are controlled by this object. For example, if the object is a damper, it has a *FlowFunc* instance with the medium property as *MediumTypes.Air*, and also a *ControlFunc* instance with the controlled property represented by the *PropertyTypes.Flowrate*. The *EnerExchangeComp* class is a subclass of the *TransportComp* class. It specifies the types of components that use another medium to conduct energy exchange. A coil is one example of this since it exchanges energy between the supply water and the transported air.

This taxonomy provides an extensible way for representing HVAC components. For example, new sensor types can be created by adding a new subclass to the *Sensor* class and specifying the type of property that the sensor measures. The types of properties can also be extended by adding new items to the enumeration *PropertyTypes*. The components, such as valve, air diffuser and radiator, can be represented by creating new subclasses of the *TransportComp* class or *EnerExchangeComp* class. This proposed functional taxonomy is able to represent all HVAC components listed in Table 1. Using the information represented in this taxonomy, it is possible to interpret the functions of the HVAC components and reason about their relationships. Section 3.5 provides a detailed example of using this taxonomy to reason about the functional relationships among the components in the example shown in Figure 3.

3.5 Prototype development and testing

To verify that the taxonomy described in Section 3.4 can enable the automated reasoning of functional relationships among HVAC components, a prototype was developed and tested with the example shown in Figure 3. As shown in Figure 5(a), the space and HVAC components are modeled in the *Autodesk Revit MEP* software package and exported in IFC format. The exported IFC model did not specify the IFC classes corresponding to some of the HVAC components. For example, sensors are exported as *IfcBuildingElementProxy*, instead of *IfcSensor*. Therefore, we developed a wrapper in the prototype to automatically transform these classes into the corresponding IFC classes and assign the functional information to them. The wrapper also maps *IfcPort* instances into the instances of *Port* class. Figure 5(b) shows part of the implemented taxonomy in this prototype.

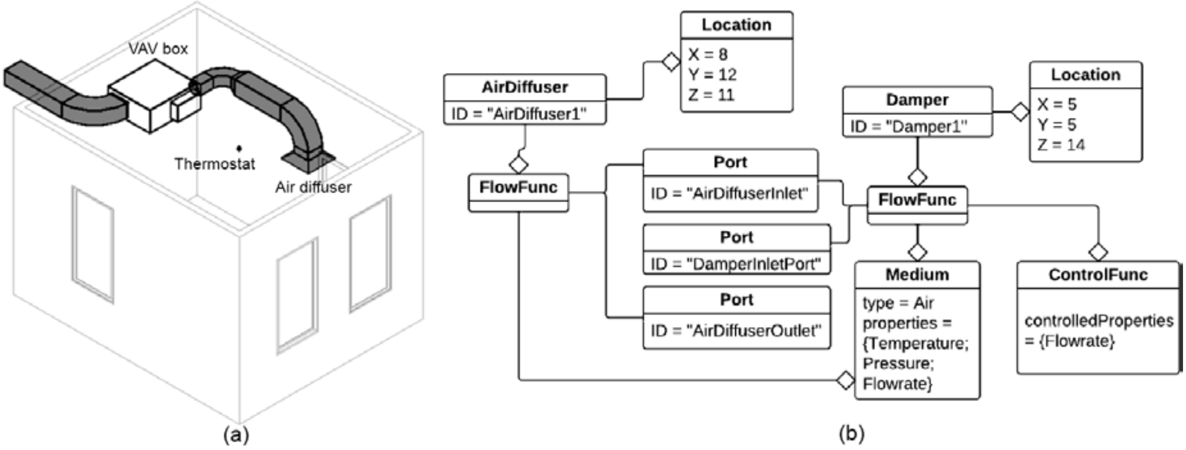

Figure 5 (a) Screenshot of the Revit model used in the prototype; (b) Examples of the implementation of proposed taxonomy

A reasoning mechanism was developed to query the components which are related to certain functions of the HVAC systems. The query example described in the motivating case study (Section 2) is used to explain the mechanism. The system operator inputs the space ID and the medium of interest, which in this case is air. The search for the functional relationships is done by navigating the topological relationships of the HVAC components using the instances of *Port* class. The algorithm starts by identifying the ports that are connected to the space and transfer air. For instance, the port connected to the air diffuser will be identified. The algorithm will then check whether this component is an instance of the Sensor class or has instance of *ControlFunc* class or not. If so, this component is recognized as a relevant HVAC component. The algorithm will iteratively search all components that are connected to the identified components using ports. The results of this test are shown in Table 2.

HVAC component	Function type	Medium	Property
Damper	Control	Air	Flow rate
Temperature sensor	Measure	Air	Temperature
Temperature set-point	Set-point	Air	Temperature

Table 2 Results for the functional query

This prototype shows that using the proposed functional taxonomy, the process of identifying the functional relationships among the HVAC components can be automated using computerized reasoning mechanisms.

4. CONCLUSIONS

This paper has shown the needs for a computerized approach that generates the functional relationships among HVAC components to support O&M tasks. By classifying the functionalities of HVAC components, this paper demonstrates that the functional relationships among HVAC components can be reasoned about using their spatial relationships and the identified component functions. An extensible taxonomy of functions of typical HVAC components has been developed and reported on in this paper so that this information can be accessed and reasoned about automatically. A prototype application was implemented to test the feasibility of the envisioned approach.

The prototype tested the proposed approach using a small portion of a HVAC system with five different components. To test the extensibility of the taxonomy and the correctness of the reasoning mechanism, in the next step of this research, we will test the prototype further with different types of HVAC systems that are deployed in various facilities.

ACKNOWLEDGMENTS

The authors would like to acknowledge and thank the IBM Corporation for the grant that supported the research presented in this paper.

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