Towards automated HVAC controls commissioning: Mechanisms to identify temperature and flow related functions of AHU components

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Abstract

Commissioning (Cx) of heating, ventilating, air conditioning (HVAC) systems has emerged as an effective sustainable practice to ensure high performance of these systems during operation. According to a DOE report, HVAC systems used 62% of the energy consumed by buildings in the US in 2011. It was also reported that controls related issues resulted in wastage of 50% of the HVAC energy consumption in 2011 (around 10% of total building energy consumption). Incorrect implementation of controls is a very common issue that can be traced back to improper representation of design intent of controls in the sequence of operations (SOOs). SOOs are currently represented through textual narratives that cannot be completely and accurately interpreted for comparison against the implemented controls during Cx. As a result, incorrectly implemented controls may remain undiagnosed, resulting in inefficient operation, energy wastage or both.

Currently, there is no guideline that can be used to identify the information to be included in SOOs. ASHRAE GPC 36 provides SOOs for 13 AHUs and ASHRAE Guideline 13 provide one sample SOOs, but they both do not list specific information to be included in SOOs. OpenBuildingControl is a research project to automatically implement the SOOs from ASHRAE GPC36 and simulate them through Spawn of EnergyPlus (SOEP) simulation engine. Even with all these efforts, there is still a need for a generalizable approach for identifying the information to be included SOOs for any AHU configuration, including the ones not included in ASHRAE GPC36. This paper describes a generalized way of identifying information items to be listed in SOOs. This approach incorporates functional and topological reasoning mechanisms to identify all temperature and flow related control processes within an air handling unit (AHU) and all components that influence each control process in a generalized way, regardless of the configuration of specific AHU.

Keywords –

HVAC Controls Commissioning, HVAC Controls Design Intent, HVAC Controls Information Requirements, HVAC Sequence of Operations, Building Information Modeling

1 Introduction

Commissioning of heating, ventilating, air conditioning (HVAC) systems is a formal step by-step process of verifying that a building is designed, constructed, and operated according to an owner's project requirements. From the energy performance perspective, commissioning of HVAC systems is important to ensure that these systems are installed to meet the heating/cooling needs of interior spaces and use energy optimally. Traditional commissioning of HVAC systems verifies a given design through various project phases and ensures that the correct system components are installed and are operational according to design documentation.

The documentation of HVAC controls is traditionally done through textual narratives called, sequence of operations (SOOs). A previous study related to this research identified several categories of challenges in accurately interpreting the design intent of controls from these narratives [12]. The identified challenges were classified into five categories: 1. Missing controlling/controlled parameters; 2. Missing set points; 3. Missing control logic; 4. Inconsistent values from multiple information sources; and 5. Missing information items. Due to these challenges, it may not be possible to accurately interpret the design intent of HVAC controls for verification during commissioning. And HVAC controls, which are not commissioned properly, will likely result in energy wastage, occupant discomfort or both.

This paper presents an approach to generate a customized list of all control processes related to air flow and air temperature within an AHU. Further, a list of all components that influence each control process that need to be described in SOOs is also generated to support commissioning. The reasoning mechanisms rely on a building information model (BIM) of a given AHU and identify all control processes related to air flow and air temperature using the types of sensors and actuators in the model. Further, the developed approach reasons with the inherent control function of components (like temperature controlling components, flow controlling components, etc.) and their topological sequence to identify all components that influence each control process. At the end, it outputs a checklist that states all control processes along with a list of all AHU components that influence each control process.

These reasoning mechanisms were implemented in a prototype that takes the BIM of an AHU as an input and generates a checklist of all temperature and flow related control processes with the AHU and all components that influence each control process. The paper provides the results of the initial experiments conducted over a case study project.

2 Background

The primary function of an AHU control system is to maintain ambient parameters of a space at pre-determined set points. These parameters such as temperature, flowrate, etc. controlled by an AHU are called controlled variables. A component like valve, damper, etc. that reacts to a signal is a controlled device. A series of actions, induced by controlled devices to manipulate controlled variables related to air or water, is called a control process. The role of controlled devices within a system depends on their inherent functionality. The roles of AHU components relevant to this study are - to enable movement of air/water through the system (flow-moving); to control the movement of air/water through the system (flow-controlling); and to enable transfer of energy between two different air/water streams in a system (energy-conversion). Each controlled device may also influence more than one control process within a system through its interactions with other system components. For example, a hot water pump next to a heating coil influences the control of hot water flowrate through the pump directly and indirectly influences the control of air temperature due to its interaction with the heating coil. This study emphasizes the interdependence of a component's inherent functionality and its impact on other control processes due to its topological relations relative to other components in the system. To ensure that the controls are accurately verified during commissioning, this information about each components' inherent functionality and indirect impact on other control processes needs to be captured in SOOs. The following sections summarize various points of departure for this study.

2.1 Previous research related to information requirements of HVAC SOOs

2.1.1 Standards and Guidelines

While no industry standard exists in identifying information requirements for HVAC SOOs, there are several guidelines published by ASHRAE that provide guidelines to generate SOOs.

ASHRAE Guideline 13, 2014 [2]:
Summary: This guideline provides suggestions in developing specifications for Direct Digital Controller (DDC) systems for HVAC control applications and provides guidance system architecture, input/output structure, communication, program configuration, system testing and documentation.
Gaps in standard/guideline: 1. This guideline does not assist mechanical designers in verifying the completeness of SOOs; 2. It does not guide mechanical designers to identify information items to be included in SOOs.

SOOs for common HVAC systems, ASHRAE, 2005[3]:
Summary: This document includes a set of 28 SOOs for various AHU configurations. Each SOOs has text version, control schematic diagram, object lists and control model summary for the AHUs.
Gaps in standard/Guideline: 1. It does not provide guidance about adapting the SOOs for other types of AHU configurations; 2. Only focuses on SOOs for AHUs and no other components of HVAC systems; 3. Does not provide guidance of testing the implemented controls based on these SOOs.

ASHRAE RP-1455 SOOs (ASHRAE GPC-36, 2018) [1]:
Summary: This specification contains a set of 13 SOOs for air distribution and terminal variable volume systems. The document contains: (a) list of hard-wired points; (b) control diagrams; (c) sequence of operations; (d) programming parameters, settings and variables for the systems.
Gaps in standard/guideline: 1. It does not provide information of the approach used to identify the information items represented in the document for extending the document to other types of systems; 2. It does not provide guidance for testing the implemented controls based on these SOOs; 3. The findings of this research project were not validated to be generalized.

2.1.2 Previous research studies

Several researchers acknowledged many challenges involved in interpreting HVAC controls' design intent from SOOs and addressed various aspects of these issues. Using the Function-Behavior-Structure (F-B-S) framework proposed by [7], the information requirements of SOOs from the past research was categorized and summarized in Table 1. Examples of information items for each category of the F-B-S framework according to previous researchers are listed in bold in the second column in Table 1.

Table 1. Information requirements of SOOs based on Function-Behavior-Structure framework

Category	References
Functional requirements	**E.g.: Be time efficient, Provide comfort, etc.**
Static information items	[4] [9] [15] [16]
Behavioral requirements	**E.g.: Heat absorption rate, response time, etc.**
Run-time information items	[10] [11]
Energy performance related information items	[10] [11]
Structural requirements	**E.g.: Geometrically interconnected components, Logically and physically interconnected components, etc.**
Relational information items	[9] [13] [15]
Constraints and heuristic information items	[5] [8]

It is required that the SOOs narrate about all control processes and relevant controlled variables and controlled devices to clearly convey the controls' design intent. Currently, as there is no formal approach to identify all the information items to be included in the SOOs, the mechanical designers are unable to verify the completeness of SOOs effectively. Hence, there is a need for a generalized approach to identify all the information items to be included in SOOs of a given HVAC system to validate the completeness of SOOs. The following sections describe the proposed research approach and reasonings that were developed to address this need.

3 Research Approach

Since the reasoning mechanisms and data representation are interdependent, all data schemas that are currently used in the industry to represent HVAC controls design information were analyzed. Table 2 presents the coverage of data schemas to represent various controls related information items that were identified under each category listed in Table 1.

Table 2. Analysis various data schemas related to HVAC controls to represent SOOs related information items

	Information items identified under each category listed in Table 1	**IFC4***	**COBie***	**HVACie***	**BAMie***	**BRICK**	**EnergyPlus**	**gbXML***
	Static information items							
1	Type of controlled variables / devices	X		X	X	X	X	X
2	Sensor unique id	X			X	X		
3	Component unique id	X		X	X		X	X
4	Control set points and schedules	X			X	X	X	X
5	Functional role of a controlled device							
	Run-time information items							
1	Operation modes	X	X		X	X		
2	Control logic					X		
3	Sensor measurements and controlled device status					X	X	X
	Energy performance related information items							
1	Design values for controlled variables						X	X
2	Efficiency and capacity	X		X	X		X	X
	Relational information items							
1	Topological relationships	X		X	X	X		
2	Functional relationships						X	X
	Constraints and heuristic information items							
1	Impact of components on all control processes							
2	Performance limitations						X	X

**IFC4 – Industry Foundation Classes 4; COBIE: Construction Operations Building Information Exchange; HVACie – HVAC Information Exchange; BAMie – Building Automation Modeling Information Exchange; gbXML – Green Building XML schema*

As can be driven from Table 2, none of the data schemas that are currently used in the industry represent all information items to be included in the SOOs to enable automated controls Cx. This study specifically focuses on identifying all components influencing each temperature and flow control process in an AHU. This can be achieved by determining the functional role of all controlled devices in the AHU. Although none of the data schemas can currently be used to represent the functional role of components within an AHU, reasoning with other static information items can help determine this. Other static information items required to be represented in HVAC SOOs are mostly represented by IFC4 and BAMie schemas. BAMie is a model view definition of the IFC4 schema, i.e. it is a sub-set of IFC4 schema. Hence, the reasoning mechanisms to identify the functional role of components were developed for an input file represented in IFC4 format. The subsequent sections present the vision and reasoning mechanisms that were developed.

3.1 Proposed Approach

The developed approach, which automates the process of determining the identification of components that directly or indirectly impact temperature and flow control processes in an AHU, consists of two major steps as shown in the shaded boxes in Figure 1. The approach takes an AHU represented in IFC4 format with all enumerations of sensor types and distribution system types as an input and outputs a list of all control processes and all components that directly and indirectly influence each control process. For example, the hot water heating coil in the AHU shown in Figure 3 directly influences supply air temperature and the hot water pump indirectly influences the air temperature by maintaining the hot water flow.

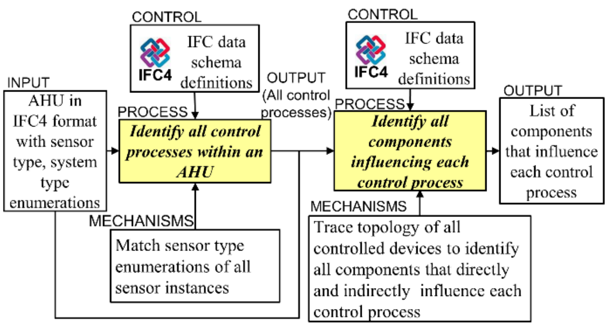

Figure 1. Proposed envisioned reasoning mechanisms

IFC4 schema has classes defined for sensors, controllers and different controlled devices. The two steps in the proposed approach rely on the sensor type enumerations, system type enumerations, component inherent functionalities and topological relationships of all components defined in the input IFC4 format file to identify each control process and components that directly and indirectly influence it. Figure 2 presents a flowchart showing the various reasonings that were developed in this study. The flowchart shows some sample results in bold-italics.

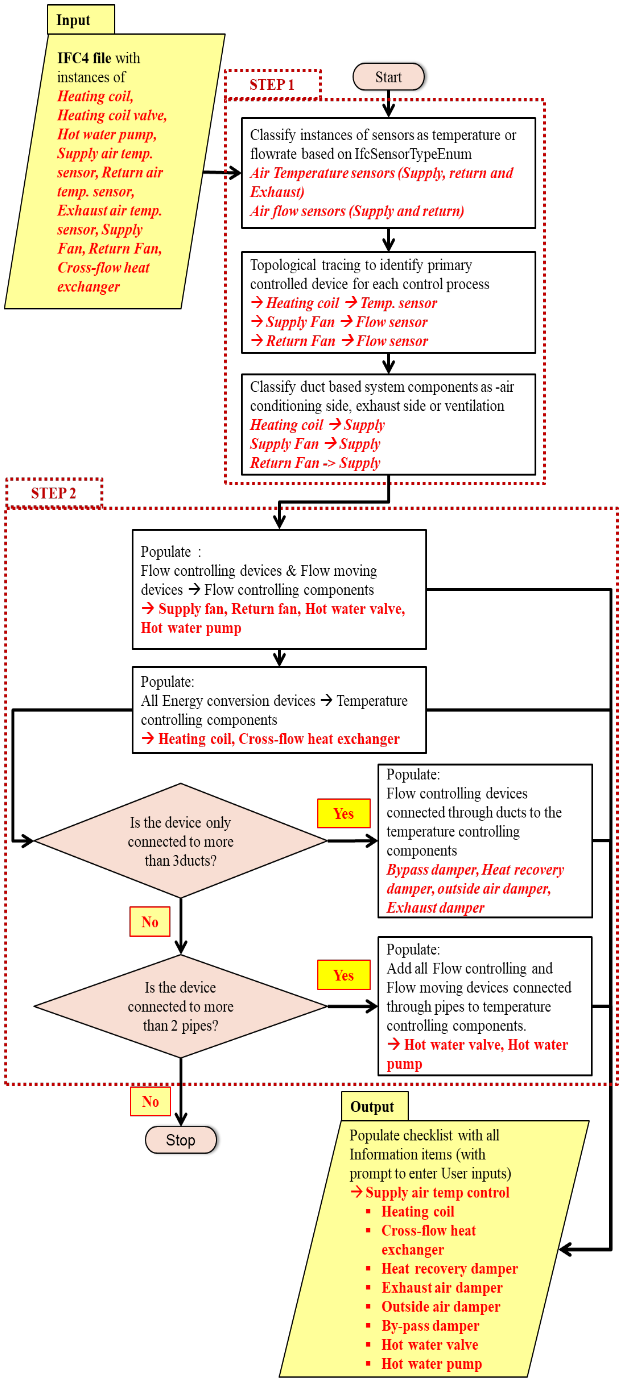

Figure 2. Flowchart showing the proposed reasoning mechanisms implemented in the prototype

Currently, many of the existing BIM authoring tools do not directly allow defining these enumerations. For the purpose of this study, enumerations of all components (IfcDistributionSystemTypeEnum, IfcFlowDirectionEnum and IfcSensorTypeEnum) within the testcase were manually populated. Figure 3 shows the AHU that was used as the test-case for this study.

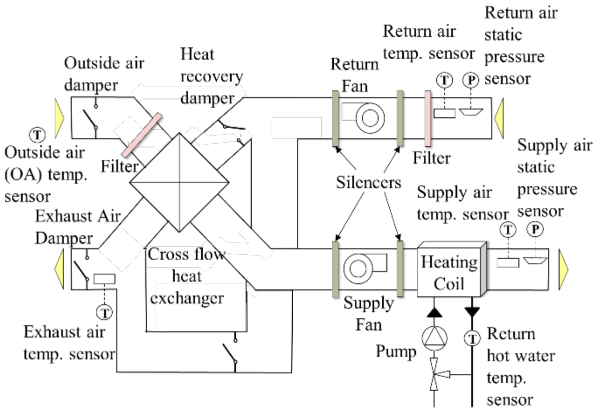

Figure 3. An AHU used as a test case for the study

3.1.1 Step 1: Identification of all temperature and flow related control processes

The first step in the proposed reasoning mechanisms is to identify all the control processes within the system. This step also involves the identification of the primary controlled devices influencing the control process and its relative location within the system to determine if it indirectly influences other control processes. For example, the supply air temperature sensor in the test case in Figure 3 is determined based on its sensor type enumeration (TEMPERATURESENSOR). Due to the relative location of the heating coil and the cross-flow heat exchanger occurring before the supply air temp sensor, it is determined to primarily impact supply air temperature control process. The reasonings are explained below:

Step 1a – Matching of sensor type enumerations for each sensor instance to identify control process types:

According to the principal of design for closed loop control systems, each control process uses the measurements from sensors at the end of a control sequence to send feedback to the controller about the controlled variable. The functioning of a controlled device is adjusted based on the feedback until the desired measurement is received from the sensor. Hence, knowing the types of sensors defined through the IfcSensorTypeEnum class helps in identifying the types of the control processes in a system. Since the scope of this study is limited to air temperature and flow related control processes, an instance of a sensor with FLOWSENSOR enumeration can be used to identify flow related control process and an instance of a sensor with TEMPERATURESENSOR enumeration can be used to identify temperature related control process. These two enumeration definitions for IfcSensorTypeEnum class are listed in Table 3.

Table 3. Enumerated item definitions for IfcSensorTypeEnum class relevant to this study in IFC4 schema

Enumeration	Definition	Reasoning
FLOWSENSOR	a device that senses or detects flow in a fluid	Match enumeration to flow control process
TEMPERATURE SENSOR	a device that senses or detects temperature	Match enumeration to temperature control process

Step 1b – Topological tracing to identify primary controlled devices associated with each sensor:

Further, knowing the topological location of the sensor with respect to other system components can help in identifying the specific control process, whose output is being measured using the sensors. This step involves tracing the sequence of AHU components to identify the energy conversion devices preceding temperature sensors and flow moving devices immediately preceding the flow/pressure sensors in an AHU. Since sensors can only measure the impact of preceding components in a control sequence, the proposed reasoning only looks for components preceding the sensors in a given AHU configuration. Also, all components are connected to each other through flow-fittings like ducts, pipes or cables. Since these flow-fittings do not directly influence the control processes, if a flow-fitting is directly preceding a sensor, the next preceding energy conversion device or flow moving device are identified respectively. The sequence of components in the AHU can be determined by the component's ports that connect to the adjacent component. IFC4 schema defines four different types of ports using IfcFlowDirectionEnum. Table 4 presents the definitions that were used in this study. SOURCE port corresponds to the outlet and the SINK port corresponds to the inlet of any component. The flow direction of air and thereby the sequence of AHU components is determined by the connections of source of a component to the sink of the adjacent component. For example, the supply air temperature sensor in Figure 3, has a duct connected to its source port. Further, the sink port of the heating coil is connected to the source port of the duct. Hence, the air flows through the heating coil to the duct to the sensor.

Table 4. Enumerated item definitions for IfcFlowDirectionEnum class in IFC4 schema

Enumeration	Definition	Reasonings
SOURCE	A flow source, where a substance flows out of the connection	Component connected to SOURCE port occurs prior in the sequence
SINK	A flow sink, where a substance flows into the connection	Component connected to SINK port occurs after in the sequence

Step 1c – Matching of distribution system enumerations and topological tracing to identify all control processes:

For each control process, once its type and the controlled devices primarily associated with it are determined, its context within the AHU (i.e., if it belongs to the supply side, return/exhaust side) is identified by matching the enumeration of the abstract class IfcDistributionSystem for each primary controlled device identified. This is required as the same type of control process can occur on the supply and the return side. For example, air flow is controlled by both the supply and return fans. All components that can be connected to ducts (since this study only involves AHU components) have three possible enumerations, based on the definitions in IfcDistributionSystemEnum. All control processes associated with components with AIRCONDITIONING or VENTILATION enumeration are classified as supply side control processes. All control processes with components with EXHAUST enumeration are classified as return / exhaust side control processes. Table 5 presents the enumerations for IfcDistributionSystemEnum class for duct-based systems used in this study.

Table 5. Enumerated item definitions for IfcDistributionSystemEnum class for duct-based systems in IFC4 schema

Enumeration	Definition	Reasonings
AIR CONDITIONING	Duct-based systems with this enumeration are meant to maintain temperature range within one or more spaces;	Match enumeration as supply side components
EXHAUST	Duct-based systems with this enumeration are meant to remove air from or more spaces;	Match enumeration as return / supply side components
VENTILATION	Duct-based systems with this enumeration are meant to either exchange or circulate outside air to spaces in a building;	Match enumeration as supply side components

3.1.2 Step 2: Identification of all components that influence each control processes

The second step of the reasoning mechanism is to identify all components that influence each identified control process in Step 1. This involves determining the inherent functionality of all components within the input IFC4 file through abstraction. For example, the supply fan is represented by an instance of IfcFan. The super-class of IfcFan is IfcFlowMovingDevice. All instances of sub-classes of IfcFlowMovingDevice influence flow related control processes based on the defined inherent functionality in IFC4 schema. Further, it is important to understand the interaction between control processes related to air flow and air temperature within an AHU. Temperature related control processes may involve direct heat transfer, air-to-air heat transfer or water/refrigerant-to-air heat transfer. While no additional components are involved for direct heat exchange, components that influence air temperature control for air-to-air and water/refrigerant-to-air heat exchange are identified through classification of component types and analyzing their configuration. The reasonings for step 2 are explained below:

Step 2a: Identification of inherent control functionality of all components through abstraction to associate with the identified control processes:

Inherent control functionality of HVAC components is defined at superclass level in IFC4 schema. Various control functionalities of components are defined as sub-classes for IfcDistributionFlowElement class. Instances of subclasses (e.g., IfcFan, IfcPump) of IfcFlowMovingDevice are used to define components that initiate the movement of fluids within an AHU. Instances of sub-classes (e.g., IfcDamper, IfcValve) of IfcFlowController are used to define components that regulate the flow of fluids through a system. All components that are instances of sub-classes of IfcFlowMovingDevice and IfcFlowControllingDevice define the occurrence of a device to control or enable flow of fluids through a system. All instances of sub-classes of IfcEnergyConversionDevice influence temperature related control processes based on their inherent functionality as defined in IFC4 schema. The other sub-classes of IfcDistributionFlowElement (e.g., IfcFlowFitting, IfcFlowTerminal, etc.) are not relevant for this study as their inherent functionality as defined by their abstract class do not influence air flow and temperature within an AHU. Figure 4 shows the relevant class hierarchy at which the inherent functionality of various components can be determined.

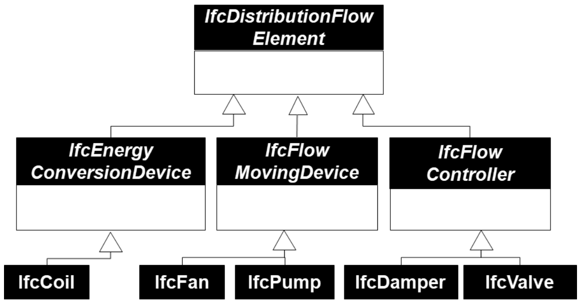

Figure 4. Subtypes of IfcDistributionFlowElement in the IFC4 schema relevant to this study

Step 2b: Identification of components influencing temperature control processes involving air-to-air heat transfer:

Air-to-air heat transfer resulting in air temperature related control processes can be identified based on the number of ducts connected to the instance of energy conversion device. Energy conversion devices can be classified as air-to-air heat transfer devices if they are connected to more than three ducts at their ports. The configuration of one air stream through an energy conversion device can have a maximum of three ducts – entering, leaving and exhaust (optional for pressure release). Hence, energy conversion devices with more than one air stream passing through them would have more than three ducts connected to them. Flow controlling devices immediately next to these air-to-air heat transfer energy conversion devices help modulate temperature of air. For example, the cross-flow heat exchanger in the test case modulates the flow air supply and return air streams. Dampers adjacent to the cross-flow heat exchanger are also used to control the supply and return air, but their purpose is to control the temperature by modulating air streams through a heat-exchanger.

Step2c: Identification of components influencing temperature control processes involving water/refrigerant-to-air heat transfer:

Water/refrigerant-to-air heat transfer resulting in temperature related control processes in an AHU can be identified if an energy conversion device is configured to be connected to a maximum of three ducts that correspond to one air stream and at least two pipes connected to it that correspond to one water or refrigerant stream. These correspond to an air stream and another stream of water/refrigerant through pipes. The first flow moving device and first flow controlling device connected to the pipe immediate after the water/refrigerant-to-air energy conversion device help modulate the temperature of air through the component. For example, the hot water heating coil in the test case enables water-to-air heat transfer to control the supply air temperature. The hot water valve and the hot water pump immediately next to the coil modulate to influence the control of temperature of air through the coil.

3.2 Prototype development and discussion

The described reasoning mechanisms were developed with the aim of identifying all temperature and flow related control processes within an AHU. Further all components that influence each control process are identified in a customized way through abstraction, classification and configuration analysis of each component. A prototype was developed with the proposed reasonings to identify the contextual functions of components in an AHU.

The prototype was created and the reasonings were verified using the test-case AHU shown in Figure 3 to see if it captured all the temperature and flow control processes and the components that directly and indirectly influence each identified control process. Table 6 presents the results identified by the prototype. Since no components precede the return air temperature sensor, no components were identified for the control process.

Table 6. Control processes and the components directly and indirectly influencing them identified by the reasoning mechanisms in the prototype

Control process identified	**Components identified to directly and/or indirectly influence the control process**
Supply air temp control	Heating coil, heat exchanger, heat recovery damper, outside air damper, by-pass damper, hot water valve, hot water pump
Return air temp control	-
Exhaust air temp control	Heat exchanger, outside air damper, heat recovery damper, by-pass damper
Supply air flow control	Supply fan, outside air damper
Return air flow control	Return fan, heat recovery damper, bypass damper, exhaust air damper

As a summary, reasoning mechanisms to identify components that directly and indirectly influence air temperature and flowrate in an AHU were developed and verified using a testcase. Future research in this study will focus on determining components that directly and indirectly influence other types of control processes within an AHU like humidity, CO2 level, etc.

4 Conclusion

This paper highlights the information items that need to be included in SOOs for HVAC systems based on the Function-Behavior\-Structure (FBS) ontology structure. FBS ontology structure is a proven robust descriptor of designs and designing process [7]. Reasoning mechanisms were developed based on function and structure ontology to identify temperature and flow related control processes within an AHU. Also, the components that influence each control process through abstraction, classification and their configuration analysis. Future research in this study will be extended to other control processes within an AHU such as humidity, CO2 level, etc. Also, future work will extend data schemas and reasoning mechanisms to enable automated extraction of all information requirements for HVAC SOOs identified in this paper.

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