ONTOLOGY DEVELOPMENT FOR LOW-ENERGY BUILDING EMBEDDED COMMISSIONING

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ABSTRACT

This paper presents the results of initial work in developing an ontology for improving information exchange and automation in building system commissioning practices. In our previous research dealing with the derivation of product models from building commissioning process models, we found that there is a need to categorize and classify information items, which are available in commissioning process descriptions. In addition, the relationship between these items should be clearly defined to establish a topological relationship between items necessary for specifying product models.

Ontology development is the way to categorize and classify domain knowledge information and items into inter-related concepts. Ontology assembles information in the form of concept hierarchies (taxonomies), axioms, and semantic relationships, which allow natural language to be presented unambiguously. A glossary (a lower form of ontology) specific to building commissioning tasks was developed as a first step. In the second step, an ontology for use in commissioning software applications was developed.

EXISTING ONTOLOGIES IN AEC/FM DOMAIN

In the context of computer science and information management, ontology is a "formal explicit specification of a shared conceptualization" of domain knowledge (Gruber 1993). The term is borrowed from philosophy, where ontology is the nature of being, existence or reality in general, as well as of the basic categories of being and their relations listed as a part of metaphysics. Ontology provides a process to categorize/classify domain knowledge information/items into inter-related concepts. Ontology assembles information in the form of concept hierarchies (taxonomies), axioms, and semantic relationships, which allow natural language to be presented unambiguously (El-Diraby and Kashif 2005).

Ontology supports the shared understanding of a domain of interest for communication between human beings or among human beings and applications by reusing formally represented knowledge (Yang et al. 2008). Many ontologies have been developed according to this concept including specialized ones like a chemical ontology (López et al. 1999) and a monatomic ions ontology (Gómez-Pérez et al. 2004). The architectural engineering construction (AEC) and facility management (FM) industries have been studying the sharing and communicating of knowledge in formal ways. Among all AEC/FM fields, the construction domain has expended the most effort in this direction.

Although the definition of ontology is clear, there is confusion about ontology-like (or controlled vocabulary) resources in the construction domain. For example, the *eConstruct* project developed the taxonomy called *bcBuildingDefinitions* in order to demonstrate the power of *bcXML*. The *LexiCon*, initiated by researchers working on this subject in The Netherlands, offers a vocabulary of terms of interest for the construction industry. There are additional vocabulary resources in the building and construction industry such as *BARbi* (Norway, reference data library) and the Standard Dictionary for construction (French, vocabulary) (Lima et al. 2007).

The industry foundation classes (IFC) data model is another standardization effort to enable the sharing of building information models to increase the productiveness of design, construction and maintenance operations (Lima et al, 2007b). According to Lima et al. (2007b), the "IFC model describes an object model with *concepts* (classes or "terms"), *relations* (as direct association or objectified relationships), and *attributes* (or properties). Ontology-like resource development for the construction sector is more active in Europe and has reached a level necessitating the development of an ontology called *e-COGNOS* to promote consistent knowledge management within collaborative construction environments (e-Cognos, 2008). E-Cognos is a project that establishes and deploys domain ontology for knowledge management for the AEC/FM sector as well as others.

The main advantage of using e-Cognos is that it incorporates an iterative approach with reliable sources such as IFC, bcXML (Lima et al. 2003) and *BS6100* (Glossary of building and civil engineering terms, produced by the British Standard Institution) (Lima et al. 2007a). Unlike controlled vocabularies in Europe, there was an attempt in North America to bring classification within a single, multifaceted approach called the *OmniClass* Construction Classification system (Lima et al. 2007a).

Among those ontologies cited above, we selected e-COGNOS as the base ontology because e-COGNOS has the distinct advantage of extensibility

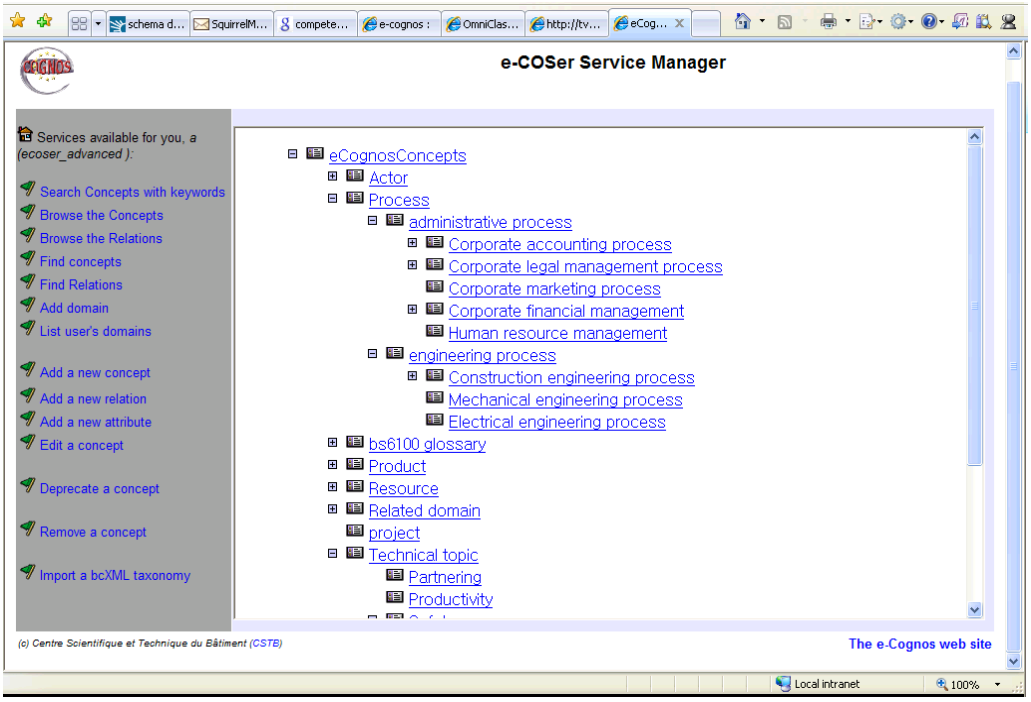

Figure 1. e-COGNOS Ontology server

through the addition of new concepts and relationship as shown in Figure 1. Other advantages of the e-COGNOS ontology include that it is compatible with the bcXML taxonomy and that the IFC 2.x kernel structure (IFC, 2007) is its backbone, thus making it IFC compatible. The motto of e-COGNOS is stated in (Lima et al. 2007a) :

"*In the context of a Project, a group of Actors uses a set of Resources to produce a set of Products following certain Processes within a work environment (Related Domains) and according to certain conditions (Technical Topics).*"

Building Commissioning (BCx) verifies that all systems and components are designed, installed, tested, and operated according to the requirements of the owner. By using this motto, BCx's definition can be translated into: "*In Context of a Project, a group of Actors (BCx agent, general contractor) uses a set of Resources (i.e. data logger) to verify a following certain Processes (Pre-functional Checklist or FPT) within a work environment (BCx) and according to certain conditions (Technical Topic).*"

The reason why OmniClass was not chosen for our research work is that it is a text-based classification requiring another process to translate formal notation and digital representation. e-COGNOS has its own ontology server developed by Java script. Another reason is that classification in OmniClass is too specific and redundant to represent embedded commissioning information. For example, the Fan Coil Unit concept can be found from Product→ Climate Control (HVAC)→HVAC Distribution Device→Water Heated & Cooled Terminal & Cooling Unit→Fan coil Unit. The classification in OmniClass focuses more on usage of equipment rather than representing the product information itself.

GLOSSARY

Our research aims to create information assistance for commissioning low energy buildings throughout their life-cycle. We call our approach embedded commissioning (ECx) because information used throughout this process is intended to be *embedded* in the product models that sustain interoperability between successive building life-cycle stages (Akin et al., 2007).

As a first step, a glossary for commissioning was built by extracting terms from well-established sources such as pre-functional checklists and functional performance test protocols from PECI (2009), ASHRAE guidelines (2005) and the BCx handbook (U.S. DOE, 1998) (Table 1).

Table 1. Glossary of ECx terms (partial list)

Acronym	**Concept**
AHU	Air Handling Unit
CCV	Cooling Coil Valve
CD	Condenser
CDP	Condenser pump
CH	Chiller
CHW diff press Spt	Chiller Difference Press setpoint
CHWP	Chilled water pump
CHWST	Chilled water supply temperature
CxA	Commissioning Agent
CC	Control Contractor

ONTOLOGY DEVELOPMENT FOR EMBEDDED COMMISSIONING

The scope of our ECx ontology (ECx-O) is limited to represent concepts, relations, and axioms used in BCx protocols for acceptance and post-construction BCx phases before it is embedded in the product and process model. It focuses on the representation of the BCx process and product information. The concept of cost/benefit generated during commissioning was excluded from developing ECx-O.

The concepts were then categorized into e-COGNOS main domains: *Process*, *Project*, *Product*, *Actor*, *Resource* and *Technical Topic*. Due to technical problems regarding installation of e-COSer (ontology server for e-COGNOS) and licensing issues, it was difficult to evaluate the full functionalities covered by it, including: how to search for concepts with key word, browse the relations, find concepts, and add new concepts and relationships. To circumvent this problem, we decided to use the Protégé ontology editor[1] to input concepts and relationships in ECx-O. This tool is popularly used in ontology development in various research studies. We believe, one of the reasons for this is the fact that it can save and export an ontology through various ontology formats used in the field: such as Resource Description Framework (RDF)/XML Web Ontology Language(OWL)/XML, CLIPS and Turtle.

The major aspects of an ontology we implemented in ECx-O include *Project*, *Process*, *Product*, *Resource*, *Actor* and *Technical Topic*. Below we describe each of them.

Project Concept

Based on the analysis of the sources listed in section "GLOSSARY", the term "Project" occurs only in the cover sheet of the ASHRAE-Cx protocol to identify the name of the facility. There is no project concept in e-COGNOS that can be used in ECx-O. However, the previous research (Türkaslan-Bulbul 2006) found that the BCx protocol for a laboratory building is totally different than that of a dormitory even though both buildings were located on university campuses. Resources - such as the PECI protocol for ECx-O - do not support the usage of different BCx protocols for different building types. Therefore, the Project concept is proposed to be an extension to the e-COGNOS concept ontology.

[1] Certain commercial products are identified in this paper in order to specify the development procedure adequately. Such identifications is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the products identified are necessarily the best available for the purpose.

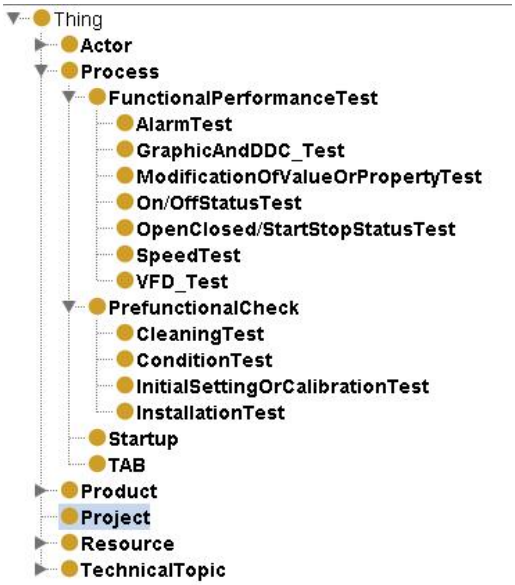

Figure 2. The Taxonomy for *Process*

Process Concept

For this project it was decided to limit the commissioning scope to acceptance and post-construction phases of a project. *Process* concepts appropriate to this scope, such as *start-up*, *pre-functional checklist*, and *functional performance test (FPT)* were added to ECx-O. Through our ECx case study (Akin et al., 2007), it was discovered that the test procedure had to be customized and modified because the configuration and the environment of the equipment are significantly different from the normative information included in the FPT.

Often, the owner has his own purposes for modifying the FPT procedure for BCx. For example, if the BCx was being done during a time when the facility was occupied, the owner might want to skip the on/off test for the heating equipment since this may interrupt the occupants' work process. Consequently, it would be helpful to classify the test procedures according to their features. In previous research (Türkaslan-Bulbul 2006), the features of the test in the pre-functional checklist and FPT have been classified. We added this classification to the *Process* category. Figure 2 shows the *Process* concept.

Product Concept

Eighty-five BCx related products were identified. These products were categorized into several types: *HVAC_Component*, *HVAC_Element*, and *System*. *HVAC_Element* includes *HeatingElement*, *VentilatingElement*, and *CoolingElement*. Some elements perform multiple functions (heating or cooling); such as *FanCoilUnit*. *Condenser* can be used for heating, cooling, and ventilation. These cases are categorized directly under *HVAC_Element* instead of heating, cooling, or ventilating.

The system and HVAC element taxonomy is shown in Figure 3.

Figure 3. The Taxonomy of the *Product*

Resource, Actor & Technical Topic

Resource is a reference document or equipment used during commissioning. Examples are shown in Figure 4. *Actors* involved in BCx are defined, as shown Figure 5. *Technical Topic* is related to attributes, parameters, constraints checked during commissioning. This covers domains such as electric, temperature and time related BCx (Figure 6).

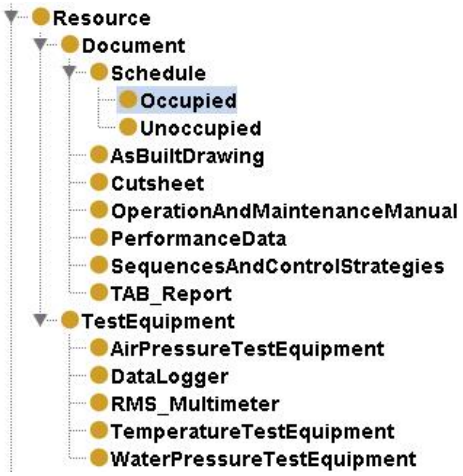

Figure 4. The Taxonomy of the *Resource*

ECX ONTOLOGY RELATIONSHIP AND AXIOM

Due to technical problems regarding installation of e-COSer (ontology server for e-COGNOS) and licensing issues, it was difficult to determine the working relationships between the concepts we implemented. In order to see the relationships between concepts, Figure 7 can be retrieved from one of the presentation files for e-COGNOS. Verbs used in the commissioning protocol are defined as "relationship" while nouns are defined as concepts in the previous step. It is similar to the object-oriented method. (Gomez-Perez 1998). The defined relationship extends e-COGNOS relations

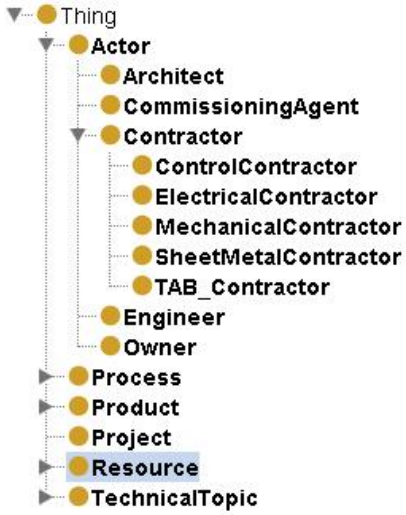

Figure 5. The Taxonomy of the Actor

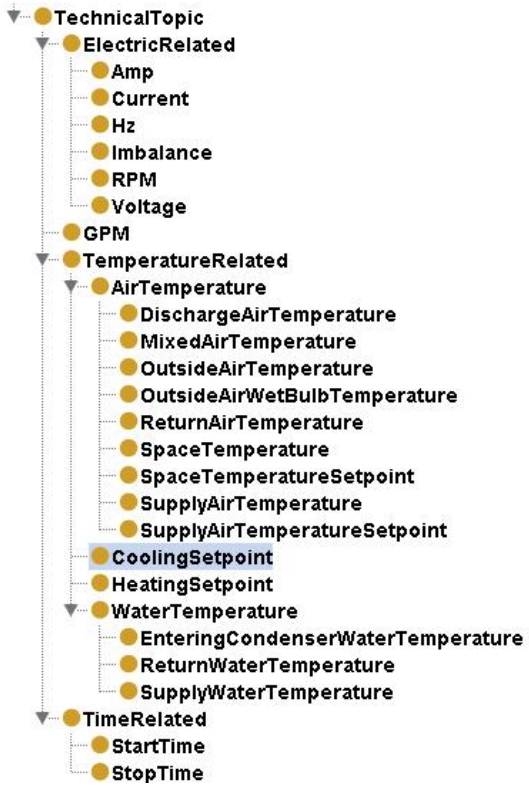

Figure 6. The Taxonomy of the *Technical Topic*

Figure 7.eCognos Relations

A total of 52 verbs were found during analysis of resources as shown below in alphabetical order: [*approve*, *attempt*, *attach*, *calculate*, *calibrate*, *cause*, *change*, *check*, *close*, *command*, *continue*, *disable*, *discharge*, *do*, *fail*, *fill*, *filter*, *have*, *include*, *incorporate*, *increase*, *interlock*, *list*, *lower*, *measure*, *modulate*, *observe*, *open*, *override*, *overwrite*, *place*, *program*, *raise*, *record*, *relief*, *remove*, *reset*, *restore*, *return*, *review*, *sample*, *set*, *shut*, *simulate*, *start*, *stop*, *submit*, *test*, *trend*, *trip*, *turn*, *utilize*, *use*, *verify*, *wait* (underlined text denotes "relationship")]

In addition to this, the type "verb" was not found in the *Resource* (PECI protocol, ASHRAE guidelines and the BCx handbook)], but is needed to define the relationship between HVAC components and elements such as "HasPart," or *Relationship* between HVAC elements like "control." Moreover, relationships may have corresponding inverse relationships. If some relationship links individual (instance) A to individual B then its inverse property will link individual B to individual A. For example, *FanCoilUnit* has part *SupplyFan* and *SupplyFan* is part of *FanCoilUnit*. The followings are added to relationship in order to show inverse relationship: :

[HasPart(←→IsPartOf),Control(←→IsControledBy), Connect(←→IsConnectedTo),Interlock(←→IsInterlockedTo)]

The meaning of the type *Axiom* in the dictionary is "a self-evident truth that requires no proof" and "universally accepted principle or rule." In an ontology, Axioms are used to constrain possible spurious interpretations of the defined terms (Gruber 1993). An ontology for ECx is extended from e-COGNOS and will inherit the concept, relationship, and the axioms from e-COGNOS which constrain the abstract level concept (*Project*, *Actor*, *Process*, *Technical Topic*, and *Resource*). A set of axioms has been developed to correspond to the following:

1. BCx results have to be *approved*, *not_approved*, *under_development*, or *under_evaluation*.
2. Each commissioning test has the owner's project requirements and specifications
3. Each commissioning test has to be performed within safety limits and operating ranges.
4. Each commissioning test has a commissioning agent (CxA) to perform the test and prove it.

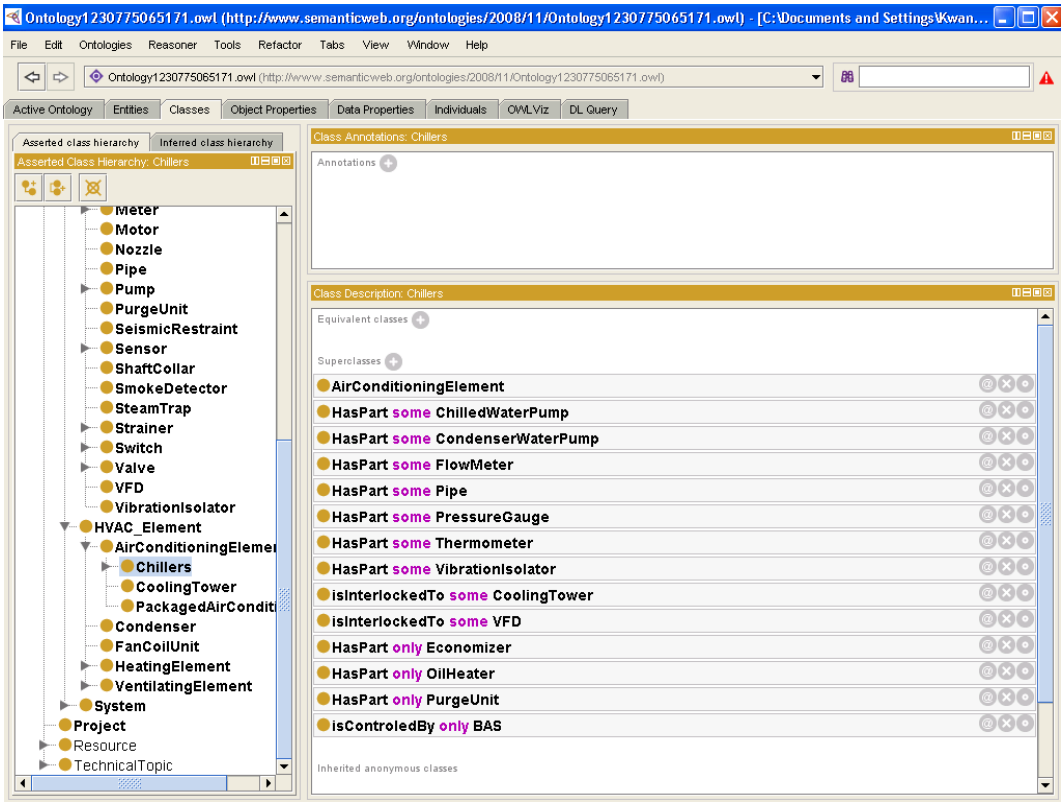

Figure 8. Screen shot of Protégé after applying restriction

Having created *Concept* and *Relationship* types in ECx-O, we use them to describe and define ECx –O classes. This can be done to set existential and universal restrictions by using "relationship to the concept" function in Protégé. The Protégé manual defines the meaning of existential and universal restrictions as "Existential restrictions describe classes of individuals that participate in at least one relationship along a specified property to individuals that are members of a specified class." In Protégé 4, the keyword 'some' is used to denote existential restrictions. Universal restrictions describe classes of individuals that for a given property only have relationships along this property to individuals that are members of a specified class. In Protégé 4, the keyword 'only' is used. Figure 8 is an example screen shot illustrating application of these restrictions to a functional performance test for *Chillers*.

HVAC components (i.e., VAV Box) connect to *HVAC_Element* (i.e. AHU) through the "*Has Part*" relationship. *Relationship* between HVAC elements are represented by the "*Is interlocked to*" relationship. As shown in Figure 8, chiller has parts of *ChilledWaterPump*, *Condenser WaterPump*, *FlowMeter*, *Pipe*, *PressureGauge*, *Thermometer*, *VibrationIsolator*, *CoolingTower*, *Economizer*, *OilHeater*, and *PurgeUnit*. "Some" and "only" is used to indicate the number of components or elements related to the main elements. *BAS* controls *Chiller* so that *Chiller* is controlled by only one building automation system. The following partial code (Figure 9) is a result of exporting Figure 8 in XML format.

This XML of ECx-O can be exported to provide infrastructure for describing and sharing commonly used BCx data between different applications.

```
<owl:Class rdf:ID="Chillers">
    <rdfs:subClassOf rdf:resource="#AirConditioningElement"/>
    <rdfs:subClassOf>
      <owl:Restriction>
        <owl:onProperty rdf:resource="#HasPart"/>

        <owl:allValuesFrom rdf:resource="#OilHeater"/>
      </owl:Restriction>
    </rdfs:subClassOf>
    <rdfs:subClassOf>
      <owl:Restriction>
        <owl:onProperty rdf:resource="#isInterlockedTo"/>
        <owl:someValuesFrom rdf:resource="#VFD"/>
      </owl:Restriction>
    </rdfs:subClassOf>
    <rdfs:subClassOf>
      <owl:Restriction>
        <owl:onProperty rdf:resource="#HasPart"/>
        <owl:someValuesFrom rdf:resource="#VibrationIsolator"/>
      </owl:Restriction>
    </rdfs:subClassOf>
    <rdfs:subClassOf>
      <owl:Restriction>
        <owl:onProperty rdf:resource="#HasPart"/>
        <owl:someValuesFrom rdf:resource="#CondenserWaterPump"/>
      </owl:Restriction>
    </rdfs:subClassOf>
    <rdfs:subClassOf>
      <owl:Restriction>
        <owl:onProperty rdf:resource="#isControledBy"/>
        <owl:allValuesFrom rdf:resource="#BAS"/>
      </owl:Restriction>
    </rdfs:subClassOf>
    <rdfs:subClassOf>
      <owl:Restriction>
```

Figure 9.ECx-O in XML format

VALIDATION OF ECX-O

As a partial check on the completeness and validity of the ontology it was applied to a real building commissioning project that was not used as part of the development source material but for which detailed information was available. This project

was the Posner Center, a conference and rare books facility at Carnegie Mellon University.

Three commissioning protocols used in this facility were examined, one each for the chilled water system, the hot water system, and the air handling units. The terms used in these three commissioning protocols were extracted and used to test the concepts and relationships defined in ECx-O. Tables 2, 3 and 4 summarize the results of attempting to match the concepts and relationships in the Posner Center commissioning protocols with theECx-O ontology.

Table 2. Number of ECx-O Matches for the Chilled Water System Commissioning Protocol

	Concept		Relationship	
	No.	%	No.	%
Full Match	9	50%	6	50%
Partial Match	7	39%	4	33%
No Match	2	11%	2	17%
Total	18	100%	12	100%

Table 3. Number of ECx-O Matches for the Air Handling Unit Commissioning Protocol

	Concept		Relationship	
	No.	%	No.	%
Full Match	23	46%	13	59%
Partial Match	11	22%	3	14%
No Match	16	32%	6	27%
Total	50	100%	22	100%

Table 4. Number of ECx-O Matches for the Hot Water System Commissioning Protocol

	Concept		Relationship	
	No.	%	No.	%
Full Match	11	41%	7	64%
Partial Match	11	41%	2	18%
Not Match	5	19%	2	18%
Total	27	100%	11	100%

The commissioning protocols for the chilled and hot water systems had fewer steps and were less complex than the AHU commissioning protocol. The ECx-O coverage percentage for the chilled and hot water systems is higher than for the AHU protocol. The reason for picking these cases is that they represent each HVAC system in the building However, there are repetitive concepts and relationships in the three protocols. We put these together and tested them against the ECx-O. Table 5 shows the coverage of these for Posner Hall.

Table 5. Number of ECx-O Matches for AHU, Chilled and Hot Water System Protocol

	Concept		Relationship	
	No.	%	No.	%
Full Match	26	41%	16	64%
Partial Match	21	33%	4	16%
Not Match	16	25%	5	20%
Total	63	100%	25	100%

As shown in the above tables, the coverage of ECx-O is between 75% ~ 80% including partial matches, These kinds of matches are categorized as partial match because;

- A subclass is missing in the ECx-O (e.g., reheat coil is not defined under coil)
- An attribute is missing in the ECx-O (e.g., functional role of pump is not defined such as primary or lag pump)
- A synonym is missing in the ECx-O (e.g., operation and control system can be replaced with building automation system, energize or de-energize can be replaced with start or shut)

CONCLUSION

An ontology for commissioning was developed to improve information and automation in building system commissioning practice. This work will help embed commissioning information correctly in the product model by defining the meaning of each word (concept), relationship and axiom used in BCx.

ECx-O covers 75~80% of terms used in the protocols for HVAC system commissioning that were examined. To have a workable ontology, the remaining 20~25% of concepts and relationships should be identified and represented in ECx-O. The missing 20~25% of the ontology might happen because the perspective of BCx can differ between parties involved, e.g., the commissioning agent and the owner. For this reason multiple perspectives should be included in developing an appropriate ontology. As the work progresses and attempts are made to adapt it to the requirements of a broader set of commissioning processes it is anticipated that the ontology will need to be modified

FUTURE WORK

To date we have defined terms used in BCx and developed ECx-O in order to improve interoperability in the AEC/FM domain. The prototype for ECx is going to be developed based on term, relationship, and axiom we defined here. The BCx data will be carried through XML format for the production into communication and will be used in BCx reports or any internet compatible application to show the result of commissioning. In order to utilize

the prototype, we will expand and test the ontology by using a broader range of case studies, applying the ontology to a set of FPTs and expanding it to include the needs of FPTs.

ECx-O will be tested against IFC for interoperability and exchangeability. Assessment of IFC coverage will be done to compare the concept and relationship types between ECx-O and IFC. If we observe any deficiencies that prevent the proper expression or storage of information in the BCx domain, we will propose modifications and improvements to the IFC model to enable better usage of IFC in the AEC/FM domain. We anticipate that this will be achieved through the extension of the pre-defined IFC property sets for typical HVAC equipment devices.

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