FRAMEWORK FOR AUTOMATIC CONSTRUCTION COST ESTIMATION BASED ON BIM AND ONTOLOGY TECHNOLOGY

Ma Zhiliang, Professor, mazl@tsinghua.edu.cn
Wei Zhenhua, Ph.D. Candidate, weizh04@gmail.com
Department of Civil Engineering, Tsinghua University, Beijing, China

ABSTRACT

Construction cost estimation (CCE) is one of the most important tasks concerned by multi-participants in the AEC/FM industry during a project's life cycle. However, due to the traditional two-dimensional working mode, CCE is currently both time-consuming and error-prone. The advent of building information modeling (BIM) technology, as well as ontology technology, provide a potential approach to conduct automatic CCE with high efficiency and accuracy. In this paper, the basic requirements of automatic CCE based on BIM and ontology technology are firstly analyzed. Then a general framework of automatic CCE based on BIM and ontology technology is formulated and two key issues for implementing the framework are expatiated. The established framework of automatic CCE lays a sound foundation for the development of corresponding software application based on BIM and ontology technology.

Keywords: BIM, IFC, Ontology, OWL, Construction cost estimation

1. INTRODUCTION

Construction cost estimation (CCE) is one of the most important tasks concerned by multi-participants in the AEC/FM industry during a project's life cycle. With the development of information technology, many software applications have been developed and applied in CCE, which have greatly improved estimators' working efficiency. However, due to the traditional two-dimensional representation of design, estimators still have to read and extract useful information from the shop drawings or manually rebuild a three dimensional model specific for CCE and then conduct cost estimation by strictly complying with CCE specifications such as CSI or Uniformat (Ma et al. 2010). Because of working complexity and comprehending deviation during the traditional work, CCE is both time-consuming and error-prone.

The advent of Building Information Modeling (BIM) technology provides a potential approach for solving the above problem through a unique and continuously updated model during a project's life cycle (NIBS 2007). Several researches have revealed that CCE can be made more efficient and accurate by directly using BIM-based design model (Firat et al. 2010; Mashta and Alkass 2003; Shen and Issa 2010). Meanwhile, several BIM-based software applications for CCE have been developed by software vendors, e.g. *Sage Timberline* (Sage 2012), *Innovaya Visual Estimating* (Innovaya 2012), in which BIM-based design model can be imported to conduct effective cost estimation. However, the following deficiencies prevent them from being automatic and accurate. First, although construction products can be classified into assemblies or items according to user-defined conditions (Innovaya 2012), it is still a human-intensive work because the conditions have to be set to strictly comply with certain CCE specifications. Second, their quantity take-off completely depends on the imported design model without considering the effect of quantity take-off rules defined in the CCE specifications, and thus may result in an inaccurate estimate.

In order to overcome these deficiencies, in our previous research, we have discussed the semi-automatic classification of construction products into cost items and automatic quantity take-off based on BIM and relational database technology (Ma et al. 2011b). With the rapid development of semantic web, in which ontology is used to formally represent the knowledge and rules in the web domain for the purpose of making computers process information in the websites automatically (W3C 2009), it is expected that ontology can be employed in CCE domain to carry out CCE automatically.

Several studies have been carried out to develop a CCE ontology model based on BIM design model (Staub et al. 2003; EI-Diraby et al. 2005). However, few have made advantage of CCE specifications to cover the knowledge and rules in CCE domain. It is expected that using CCE specifications will facilitate the development of a CCE ontology model that includes the knowledge and rules representation for automatic CCE. Meanwhile, the bidirectional transformation between BIM data and ontology data of the CCE ontology model needs to be considered.

In this paper, the basic requirements of automatic CCE based on BIM and ontology technology are firstly analyzed. Then a general framework of automatic CCE based on BIM and ontology technology is formulated and two key issues, i.e. the CCE ontology model based on CCE specifications, and the bidirectional transformation between BIM data and ontology data of the model, are expatiated to implement the framework.

2. REQUIREMENT ANALYSIS OF AUTOMATIC CCE BASED ON BIM AND ONTOLOGY TECHNOLOGY

2.1 Feasibility of integrating BIM and ontology technology in CCE domain

BIM facilitates information sharing between different phases during a project's life cycle (NIBS 2007), including the design and CCE phases. Theoretically, information in BIM-based design model can be directly shared in CCE, thus it can greatly reduce estimators' workload of reading the shop drawings or rebuilding the 3D model, as well as the probability of making extra errors.

Ontology can be used to formally represent knowledge as a set of concepts and the relationships between them in a certain domain (Wikipedia 2012). In other words, it provides a structure for organizing information for a certain domain, thus can be employed to make up for the deficiencies of immature application of BIM in the CCE domain (Ma et al. 2011a). Further, with its reasoning capability based on domain knowledge, ontology is expected to enable automatic CCE.

2.2 Basic requirements of automatic CCE based on BIM and ontology technology

Through a comprehensive investigation on the practice of CCE, the basic requirements of automatic CCE based on BIM and ontology technology are summarized as listed in Table 1. It should be noted that a preliminary study on the functions corresponding to the 5th and 6th requirements in Table 1 has been carried out in our previous research, and the semi-automatic classification of construction products into cost items and automatic quantity take-off have been realized (Ma et al. 2011b).

Table 1: Basic requirements of automatic CCE based on BIM and ontology technology.

No.	Basic requirement	Description
1	Knowledge representation of CCE domain based on ontology technology	The concepts and relationships involved in CCE domain should be represented based on ontology technology, which thus provides a structural model for organizing information for CCE.
2	Rules representation of CCE domain based on ontology technology	The rules involved in CCE domain should be represented based on ontology technology, including the rules for classifying construction products into cost items and for quantity take-off.
3	Bidirectional transformation between BIM data and ontology data	BIM data of the design model should be reorganized and transformed into corresponding ontology data according to knowledge representation of CCE domain; and after reasoning, ontology data should be back-transformed into BIM data for information sharing in the afterward phases.
4	Intelligent acquirement of construction information	Construction information that is not included in design model, e.g. construction methods and construction techniques, should be intelligently acquired from the project's construction planning documents or the history data of prevenient projects.
5	Automatic classification of construction products into cost items	With the reasoning capability of ontology, construction products can be classified into cost items automatically by computers based on the ontology-based knowledge and rules representation of CCE domain.
6	Automatic quantity take-off	Spatial relationships among construction products, e.g. intersection, opening and subsidiary, should be automatically dealt with according to corresponding rules in order to take off accurate quantities.

3. FRAMEWORK OF AUTOMATIC CCE BASED ON BIM AND ONTOLOGY TECHNOLOGY

According to the basic requirements of automatic CCE based on BIM and ontology technology, a general framework of automatic CCE based on BIM and ontology technology is established, as shown in Figure 1. In order to widen the applicability of the framework, the IFC standard (IAI 2007), which is the most mature and mainstream standard of BIM data, is adopted as the input data format for the design model. Besides, the OWL language (W3C 2009), which is recommended by World Wide Web Consortium (W3C) as the standard web ontology language, is used to represent the design model inside the framework to facilitate automatic CCE based on ontology technology.

Five functional modules are included in the framework, i.e. data importing, automatic classification of construction products into cost items, automatic quantity take-off, automatic price calculation, and data exporting. Two key issues for implementing the framework will be expatiated, i.e. the issue of the CCE ontology model based on CCE specification corresponding to the "CCE specification" in Figure 1, and that of the bidirectional transformation between IFC data and OWL data corresponding to the "automatic classification of construction products into cost items" module in Figure 1, in sections 4 and 5. Thus, the framework may serve as the foundation for the development of an automatic CCE software application based on BIM and ontology technology.

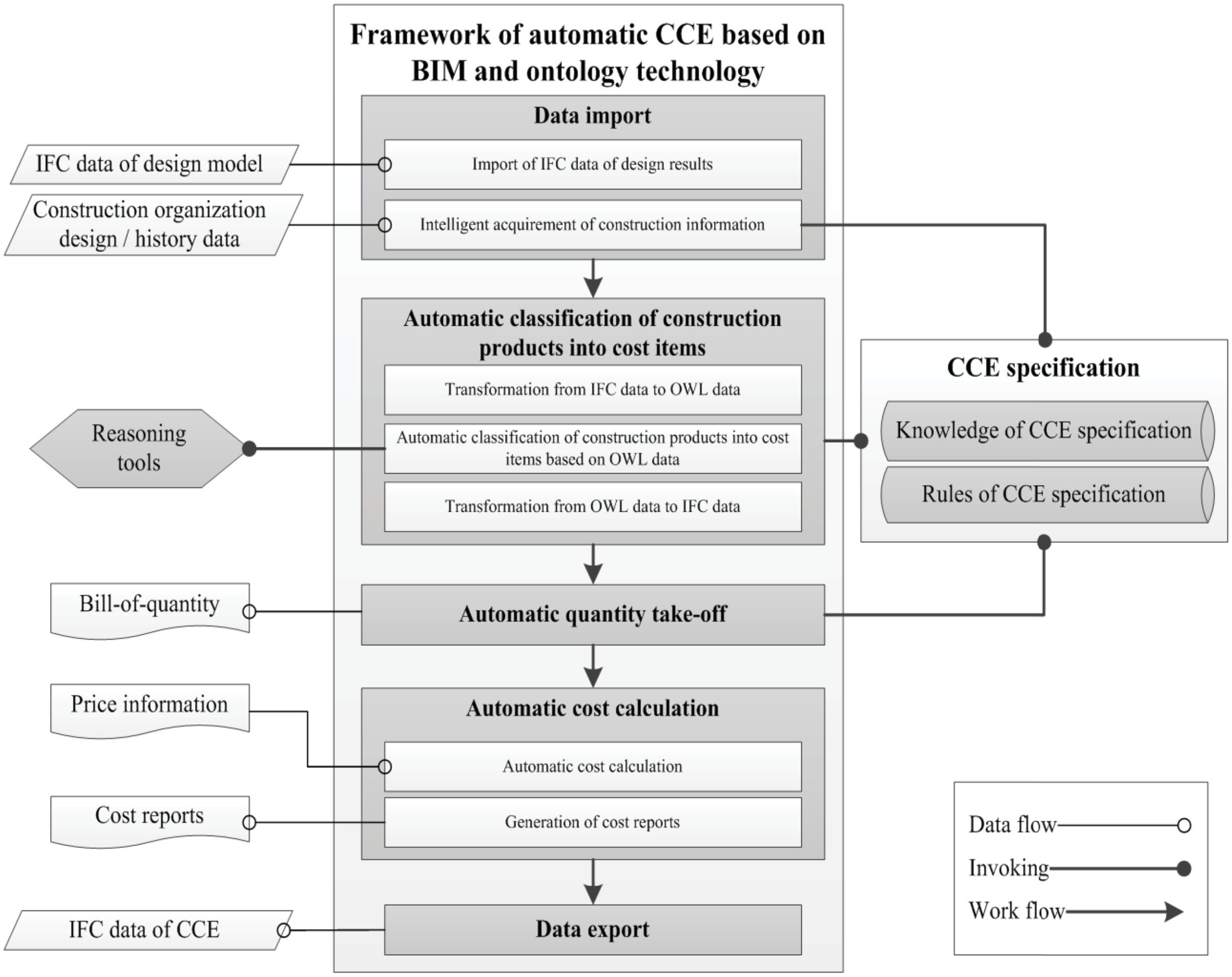

Figure 1: General framework of automatic CCE based on BIM and ontology technology

4. CCE ONTOLOGY MODEL BASED ON CCE SPECIFICATION

As a representative CCE specification, the specification "*Code of valuation with bill quantity of construction works*" in China (the BQ specification for short hereafter) (MOHURD 2008), which uses the bill-of-quantity method, is employed to establish the CCE ontology model. Considering that the bill-of-quantity method has become a well-accepted CCE method in many countries, the methodology of developing the CCE ontology model based on the BQ specification is also applicable for the other similar CCE specifications in different countries.

4.1 Knowledge representation of the BQ specifications

Hundreds of cost items are defined with specified codes in the BQ specification, each of which represents a set of construction products with certain properties. For example, the cost item "*rectangular-section column*" with the code "*010402001*" represents a set of columns whose material type is "*cast-in-place concrete*" and section shape is "*rectangle*". Through in-depth analysis on all cost items in the BQ specification, we extracted and summarized the knowledge of the BQ specification which consists of hundreds of concepts and relationships. The OWL language is employed to represent these concepts and relationships.

4.1.1 Concepts in the BQ specification

The concepts in the BQ specification are divided into three groups according to their roles, i.e. construction products, properties of construction products, and cost items. In the CCE ontology model, each concept is represented by an OWL class. Accordingly, three root OWL classes are established, i.e. *OWL:ConstructionProduct*, *OWL:Property*, and *OWL:CostItem*, whose subclasses are used to represent derived concepts. The hierarchy of OWL classes is shown in Figure 2.

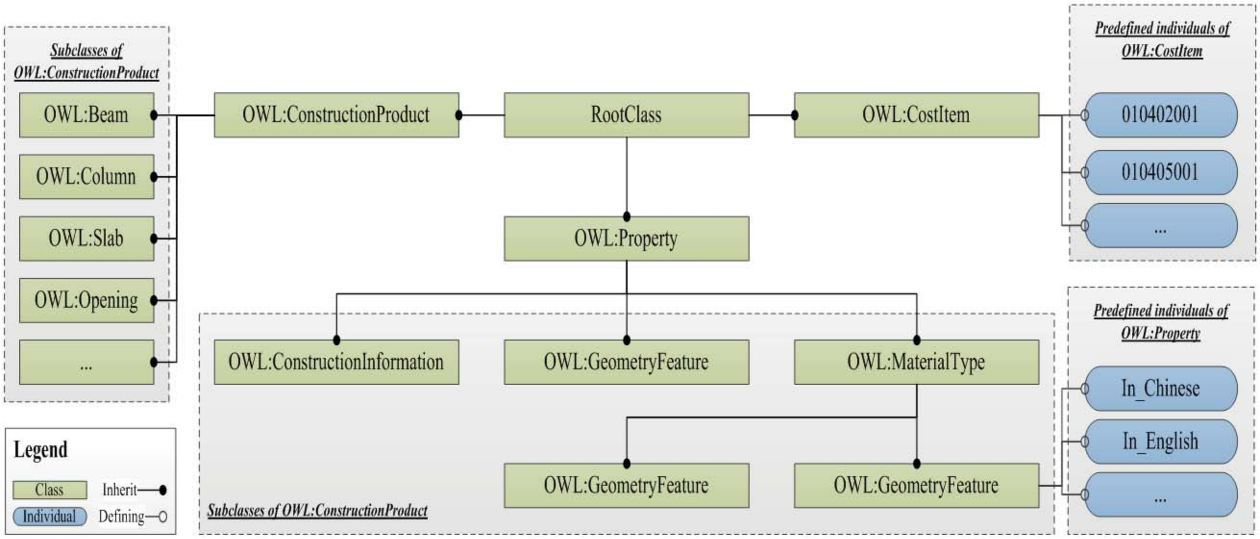

Figure 2: The hierarchy of OWL classes and predefined individuals of the BQ specification

4.1.1.1 OWL:ConstructionProduct class

Its subclasses are used to represent permanent and temporary construction products produced during a project's life cycle, such as wall, beam, slab, and formworks. For example, *OWL:Wall* is used to represent the construction products "*wall*".

4.1.1.2 OWL:Property class

Three first-level subclasses are firstly defined, i.e. *OWL:MaterialType*, *OWL:GeometryFeature*, and *OWL:ConstructionInformation*, whose subclasses are used to represent different categories of properties of construction products. Among them, *OWL:MaterialType*'s subclasses are used to represent the material type of a construction product, such as concrete and brick; *OWL:GeometryFeature*'s subclasses are used to represent the conceptual geometric feature of a construction product, such as profile and section shape; and *OWL:ConstructionInformation*'s subclasses are used to represent the construction methods or construction techniques used to produce a construction product, which usually are not included in design model and thus should be intelligently acquired from the project's construction planning documents or the history data of prevenient projects.

It should be noted that in practice, designers or estimators may use various descriptions or expressions for the same concept in the BQ specification, such as different languages, which may cause semantic problem making computers have difficulty in processing them automatically, especially in the case of properties of construction products. In order to solve this problem, for each concept of properties of construction products, descriptions and expressions widely used in practice are collected and predefined as the individuals of corresponding OWL classes, and an *OWL:SameAs* relationship is employed to relate them.

4.1.1.3 OWL:CostItem class

No subclass is defined for it. Instead, responding to each cost item in the BQ specification, an individual of *OWL:CostItem* class is predefined. For example, the individual named as *“010402001”* represents the cost item with the code “*010402001*”.

4.1.2 Relationships in the BQ specification

Each relationship in the BQ specification is defined as “*Concept 1-Relationship-Concept 2*” triples, which is used to express the relationship between the individuals of different concepts. Four aspects of relationships, i.e. property, spatiality, classification and priority, are included in the BQ specification as listed in Table 2.

Table 2: Relationships in the BQ specification.

No.	Relationship	Concept 1	Concept 2	Examples
1	Property	*OWL:Construction Product*	*OWL:Property*	***has_Material (Slab_?, Precast_concrete_?)*
2	Spatiality	*OWL:Construction Product*	*OWL:Construction Product*	Intersection: *has_IntersectedBeam (Column_?, Beam_?)* Opening: *has_Opening (Slab_?, Opening_?)* Subsidiary: *has_Subsidiary (Column_?, Bracket_?)*
3	Classification	*OWL:CostItem*	*OWL:Construction Product*	*has_ConstructionProducts (010402001, Column_?)*
4	*Priority	*OWL:CostItem*	*OWL:CostItem*	*Priority_SmallerThan (010405001, 010402001)*

* The priority relationship is completely predefined by the BQ specification but not decided by the real project.
** “Slab_?” is a certain individual of *OWL:Slab* and the notion is same for the others.

4.2 Rules representation of the BQ specification

There are two types of rules in the BQ specification, i.e. rules for classifying construction products into cost items and rules for quantity take-off.

4.2.1 Rules for classifying construction products into cost items

In fact, each of these rules is implied in a certain cost item in the BQ specification. Namely, each rule defines conditions as that construction products with specified properties can be classified into a certain cost item. In the CCE ontology model, each rule is represented by using certain conditions to reason a classification relationship *has_ConstructionProducts* between individuals of *OWL:CostItem* and those of *OWL:ConstructionProduct*. The SWRL language (W3C 2004) recommended by W3C is used to represent these rules. For example, a SWRL rule written as:

OWL:Column(?x) ∧ has_SectionShape(?x, Rectangle) ∧ has_Material(?x, Castinplace_Concrete)
→ has_ConstructionProducts (010402001, ?x)

defines how a “*has_ConstructionProducts*” relationship between the individual “*010402001*” and a column is reasoned by using certain conditions, i.e., the column’s section shape is “*Rectangle*” and the column’s material is “*Castinplace_Concrete*”. Based on these SWRL rules, by using existing reasoning tools such as Jess (SNL 2008) and Jena (Apache 2012), construction products can be automatically classified into certain cost items as long as required conditions are complete. As a result, the bill of quantity can be automatically generated.

4.2.2 Rules for quantity take-off

Rules for quantity take-off mainly define the deduction methods when the spatiality relationships exist among construction products. For the intersection relationship, the deduction method is decided by the priority relationship between individuals of *OWL:CostItem,* and the intersection part is deducted from the construction product whose corresponding cost item has a lower priority. For the other two relationships, the deduction methods are obvious.

5. BIDIRECTIONAL TRANSFORMATION BETWEEN IFC DATA AND OWL DATA

An IFC-based information model for CCE has been established in our previous research (Ma et al. 2011a). The mechanism for bidirectional transformation between the IFC data based on the model and the OWL data based on the CCE ontology model is formulated. Figure 3 uses a column as an example to illustrate the mechanism, which mainly involves the transformation between IFC instances and OWL individuals as well as the transformation between IFC relationships and OWL relationships.

5.1 Transformation between IFC instances and OWL individuals

5.1.1 Transformation of construction products

In the IFC data, construction products are expressed by the instances of the subtypes of *IfcProduct*, such as the instances of *IfcBeam* and *IfcColumn*. A set of mappings between the subtypes of *IfcProduct* and the subclasses of *OWL:ConstructionProduct* is established for the transformation, for example, the mapping between *IfcBeam* and *OWL:Beam* as shown in Figure 3.

5.1.2 Transformation of properties of construction product

For the geometry property, detailed coordinate information is stored in the IFC data to represent a construction product, while only conceptual geometric features are required in the OWL data. Thus corresponding algorithms are needed to acquire the conceptual geometric feature of a construction product from its detailed coordinate information. For example, as shown in Figure 3, the detailed coordinate information expressed by an *IfcExtrudeAreaSolid* instance is calculated to acquire the corresponding section shape, such as an *OWL:Rectangle* individual.

IfcMaterial is used to express the material information of a construction product in the IFC data, whose "*Name*" or "*ClassifiedAs*" attribute can be used to express the material type (IAI 2007). Therefore, for each *IfcMaterial* instance, the material type in the OWL data can be acquired through querying all the predefined individuals of *OWL:MaterialType* class.

5.1.3 Transformation of cost items

In the IFC data, each cost item is expressed by an *IfcCostItem* instance. Therefore, a mapping between *IfcCostItem* and *OWL:CostItem* is established for the transformation.

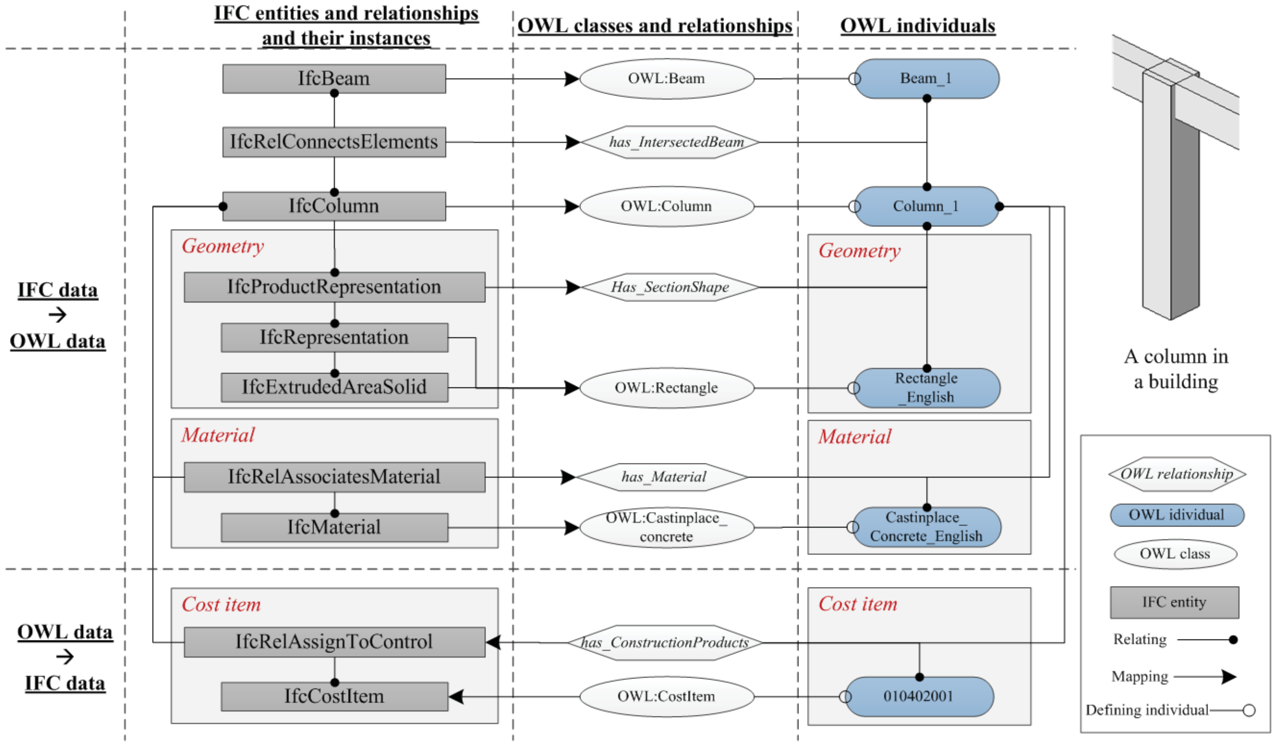

Figure 3: Bidirectional transformation between IFC data and OWL data: using a column as example

5.2 Transformation between IFC relationships and OWL relationships

This transformation mainly focuses on the first three relationships as shown in Table 2. In the IFC data, relationships are expressed as IFC relational entities, such as *IfcRelAssociatesMaterial*, or IFC entities that act as the attribute of certain IFC entity, such as *IfcProductRepresentation* that acts as the "*Representation*" attribute of *IfcProduct*. The mapping between IFC relationships and OWL relationships are listed in Table 3. It should be noted that for the spatiality relationship, the corresponding IFC instances may not be contained in real IFC data because of the imperfect support to the IFC standard in current BIM design software applications, thus algorithms for retrieving these information should be formulated according to the local placement and geometry information of construction products.

Table 3: Mapping between IFC relationships and OWL relationships.

No.	OWL relationship	Examples of OWL relationship	IFC relationship
1	Property	Geometry: *has_SectionShape*	*IfcProductRepresentation*
		Material: *has_Material*	*IfcRelAssociatesMaterial*
2	Spatiality	Intersection: *has_IntersectedBeam*	*IfcRelConnectsElement*
		Opeing: *has_Opening*	*IfcRelVoidsElement*
		Subsidiary: *has_Subsidiary*	*IfcRelProjectsElement*
3	Assembly	*has_ConstructionProducts*	*IfcRelAssignsToControl*

6. CONCLUSION

In this paper, the basic requirements of automatic CCE based on BIM and ontology technology was firstly analyzed, and then a general framework of automatic CCE based on BIM and ontology technology was established. Finally, two key issues for implementing the framework were expatiated. The findings of this paper are concluded in the following:

1. A CCE ontology model based on the BQ specification was established for automatic CCE. The methodology of developing the CCE ontology model based on the BQ specification is also applicable for the other similar CCE specifications in different countries.
2. The formulated mechanism of bidirectional transformation between the IFC data and the OWL data realizes the automatic information sharing between the design and CCE phases.
3. The established framework of automatic CCE lays a sound foundation for the development of corresponding software application based on BIM and ontology technology.

ACKNOWLEDGMENTS

This research is supported by the “*National Technological Support Program for the 11th-Five-Year Plan of China*” (No. 2007BAF23B02) and “*Tsinghua University Research Fund*” (No. 2011THZ03).

REFERENCES

Apache. "Apache Jena." http://jena.apache.org/ (6/1/2012, 2012).

EI-Diraby, T. A., Lima, C., Feis, B. (2005). "Domain taxonomy for construction concepts: Toward a formal ontology for construction knowledge." *Journal of Computing in Civil Engineering*, 19(4), 394-406.

Firat, C. E., Arditi, D., Hämäläinen, J.P., Stenstrand, J., Kiiras, J. (2010). "Quantity take-off in model-based systems." *Proceedings of CIB W78 2010: 27th International Conference*, Cairo, Egypt.

IAI (International Alliance for Interoperability). "Start Page of IFC2x3 Final Documentation." http://www.buildingsmart-tech.org/ifc/IFC2x3/TC1/html/index.htm (6/1/2012, 2007).

Innovaya. "Innovaya Visual Estimating." http://www.innovaya.com/prod_ve.htm (4/30/2012, 2012).

Ma, Z. L., Wei, Z. H., Wu, S., Lou, Z. (2011a). "Application and extension of the IFC standard in construction cost estimating for tendering in China." *Automation In Construction*, 20(2), 196-204.

Ma, Z. L., Wei, Z. H., Zhang, X. D., Qiu, S. X., and Wang P. Y. (2011b). "Intelligent generation of bill of quantity from IFC data subject to Chinese standard." *Proceedings of the 28th International Symposium on Automation and Robotics in Construction*, Seoul, Korea, 740-745.

Ma, Z. L., Zhang, X. D., Qiu, S. X., Wei Z. H., and Wang, P. Y. (2010). "Framework design for BIM-based construction cost estimating software." *Proceedings of CIB W78 2010: 27th International Conference*, Cairo, Egypt.

Mashta, S. A., Alkass, S. (2003). "Integrated cost budgeting and cost estimating model for building projects." *Proceedings of AACE International's 54th Annual Meeting*, Atlanta, USA.

MOHURD (Ministry of Housing and Urban-Rural Construction of the People's Republic of China). (2008). "Code of valuation with bill quantity of construction works (In Chinese)." China Planning Press.

NIBS (National Institute of Building Sciences). (2007). "National Building Information Modeling Standard: Version 1 - Part 1: Overview, Principles, and Methodologies." NIBS.

Sage. "Timberline Extended." http://www.sagecre.com/products/timberline_office/estimating/estimating_extended_timberliti_office_estimating_software (4/30/2012, 2012).

Shen, Z. G., Issa, R. R.A. (2010). "Quantitative evaluation of the BIM-assisted construction detailed cost estimates." *Journal of Information Technology in Construction*, 15(18), 234-257.

SNL (Sandia National Laboratories). "Jess, the Rule Engine for the JavaTM Platform." http://www.jessrules.com/ (6/1/2012, 2008).

Staub, S., Fischer, M., Kunz. J., Paulson, B. (2003). "An Ontology for Relating Features with Activities to Calculate Costs. " *Journal of Computing in Civil Engineering*, 17(4), 243-254.

W3C (World Wide Web Consortium). "OWL Web Ontology Language Overview." http://www.w3.org/TR/owl-features/ (6/1/2012, 2009).

W3C (World Wide Web Consortium). "SWRL: A Semantic Web Rule Language Combining OWL and RuleML." http://www.w3.org/Submission/SWRL/ (6/1/2012, 2004).

Wikipedia. "Ontology (information science)." http://en.wikipedia.org/wiki/Ontology_(information_science) (6/1/2012, 2012).