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BIM and ontology-based approach for building cost estimation

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ABSTRACT

This research proposes an ontological inference process to automate the process of searching for the most appropriate work items, which is limited to tiling in this case study. The proposed ontological approach can help engineers to find work items with greater ease and consistency. Suggestions are also made for further research on ways of improving the accuracy of BIM-based quantity take-off, and developing a methodology to match between work items which are expressed as different terms; however, the proposed approach emphasizes the automation of searches using BIM data to find items suitable for building elements and materials. To enable automated inference, this study establishes (1) a work condition ontology that consists of the determinants required to select work items, (2) a work item ontology, which consists of the factors defining the tiling method, and (3) semantic reasoning rules. By conducting a case study to demonstrate the proposed ontological inference process in a real-world situation, we confirm that the proposed process can provide consistent results; however, since work items differ depending on construction type and technological advancement, the work item ontology should be continually revised and updated.

The ontological inference process removes the need for the intervention of a cost estimator's subjectivity in searching for an appropriate work item. Also, if ontology is elaborately defined by the knowledge of experienced engineers, then accurate and consistent results can be obtained. In addition, the proposed process will assist cost estimators to use BIM data more easily, and it will help the expansion of BIM-based construction management.

1. Introduction

Cost estimation should be performed to calculate budget prices based on a schematic design; however, since a schematic design only provides a rough design, it is hard to obtain enough of the information needed for a cost estimation. For example, finishing material and finishing thickness can be obtained from a schematic design, but detailed information such as the specific material type and the construction method type cannot be obtained. Thus, a cost estimator infers these details from work conditions. Consequentially, a cost estimator's subjective decisions become involved in the process; however, Building Information Modeling (BIM) has been widely adopted in the building construction industry. BIM is “a new approach to design, construction, and facilities management, in which a digital representation of the building process [is used] to facilitate the exchange and interoperability of information in digital format” [1]. In the construction industry, there is a growing interest in the use of BIM for coordinated, consistent, and computable building information/knowledge management from design and construction to maintenance and throughout the stages of a building's lifecycle.

Accordingly, BIM-based cost estimation software programs, such as ToCoMan from TocoSoft, CI Estimator from CRC, and Estimator from Graphisoft, have been developed. Using such BIM-based tools, material quantity can be calculated automatically; however, any information on the work items that are related to the materials are included in the Bill of Quantity (BOQ). Theoretically, information for managing construction projects can be automatically obtained from BIM. Practically, though, the information that can be obtained from BIM is very limited unless BIM contains full information. Therefore, although BIM are used for construction management, the intervention of a cost estimator's subjective decisions cannot be avoided in searching for appropriate work items.

This research propose an ontological approach that enables the most appropriate work items to be automatically inferred in order to overcome the problem of cost estimators' subjectivity. Also, the proposed ontological inference process for cost estimation is used in the schematic design phase. To automate this inference, this study established a work condition ontology that consists of several elements: determinants to select work items; a work item ontology, which consists of the factors defining the tiling method; and semantic reasoning rules. Also, this case study demonstrates that the proposed ontologies and semantic reasoning rule can be utilized in real-world situations. Using the ontological inference process, provided that the same BIM data are available, consistent searching results of work items can be acquired. Also, the ontological inference process provides a methodology to fully

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automate cost estimation. In addition, this process can assist cost estimators to use BIM data more easily and helps the expansion of BIM-based construction management.

Section 2 briefly discusses the trends of research and the system developed for BIM-based cost estimation. Section 3 proposes ontology for the automatic inference of standard work items. Section 4, in order to demonstrate the proposed ontologies, presents a case study that confirms that the proposed ontology and semantic reasoning rule can work in real-world situations. Finally, the paper concludes by offering some final remarks in Section 5.

2. Review on related works

2.1. BIM-based cost estimation

Cost estimation is the process of predicting project costs and resource requirements. The general process of cost estimation is in Fig. 2. For cost estimation, first, estimators identify 'work conditions' such as building elements and finishing materials. These work conditions, depending on the particular project, influence costs related to required equipment, total hours of labor, or costs incurred by the need to obtain special building permits. Second, they infer what work items will be needed based on work conditions. This step requires in-depth knowledge and experience, and thus was the least structured step in the estimation process. Third, applicable unit costs are found from an external unit cost Data Base. These unit cost DB consists of type of resources, quantities of resources, and unit cost of resources for each work item (see Fig. 2). Estimators started to price each of the work items by using historical company records and catalogs that compiled cost information from previous completed projects. While most cost estimation software can perform quantity take-off or import quantity take-off data, all cost estimation software requires the use of associated and/or additional databases that contain the unit costs and other industry data needed to prepare an estimate. Fourth, estimators extracted the quantities for each of the work items from drawings. Finally, unit cost is assigned applicable work items by multiplying quantity by unit cost.

Estimation can be conducted throughout the project's life-cycle with BIM. The level of detail in the model varies depending on the project phase. BIM offers the capability to generate take-offs, counts, and measurements directly from a model. The main benefit of applying BIM-based tools to estimate project costs occurs during the quantity take-off step [1]. In particular, BIM has the following requirements [2]:

- Enough detail must be provided to generate an estimate.
- Estimators must be allowed to extract quantities of building components grouped by the company's WBS.
- For each of the cost items defined in the WBS, accurate quantities must be allowed for take-off.

At present, several BIM-based cost estimation software programs have been developed to improve the efficiency of estimators. Widely known BIM-based cost estimation programs are as follows: Innovaya Visual Estimating [3], Vico Estimator 2009 [4], Tokmo Production System [5], Success Design Exchange [6], Timberline Extended [7], and Winest Design Estimation Pro [8]. As shown in Fig. 3, which is an example of a cost estimating process using the Vico Estimator 2009, such BIM-based tools are able to take off material quantities of building elements (objects). However, selecting the most appropriate work item (in the case of Vico Estimator, the work items consist of recipe, method and resource) and matching it to the material of a building element should be processed by engineers manually.

Besides these commercial systems, there have also been research efforts to apply BIM to cost estimation. Oak et al. [9] proposed the methodology of BIM property information modeling that can support the quantity take-off of a structural element for reflecting the cost estimate feature of the public building. Kwon et al. [10] suggested ways of securing BIM quality for correct quantity take-off, which is critical for BIM applied to the building construction process and its cost estimation. Also, they established BIM modeling guides that make it possible to extract the correct quantity of take-off from BIM data. Koo et al. [11] provided a work item matching process model to help users identically recognize work items with different expressions so that they could reuse historical unit costs from the previous projects. There are two main methodologies applied in this matching process model: ontology-based term matching and term-based similarity calculation.

Staub-French et al. [12] suggested an IFC(Industry Foundation Classes)-based cost estimating system capable of directly using the results of IFC files and then automatically applying corresponding prices to accomplish the cost estimation according to the component geometries and properties. Fu et al. [13] developed a system for life-cycle cost assessment that can automatically extract cost-estimating data from the design results of IFC files, and then transfer the data to a pre-existing component of the life-cycle cost assessment. Ma et al. [14] established a framework for BIM-based construction cost estimating (CCE) software that utilized the Chinese standards. This framework was proposed, and corresponding functions were systematically analyzed. The framework laid a solid foundation for the development of next-generation CCE software. Ma et al. [15] created a discrimination model for BOQ items and the corresponding rule and semantic databases by analyzing the related Chinese standard. The IFC-based discrimination model for BOQ items was established, and a mechanism was formulated to intelligently generate BOQ from IFC data. Hartmann

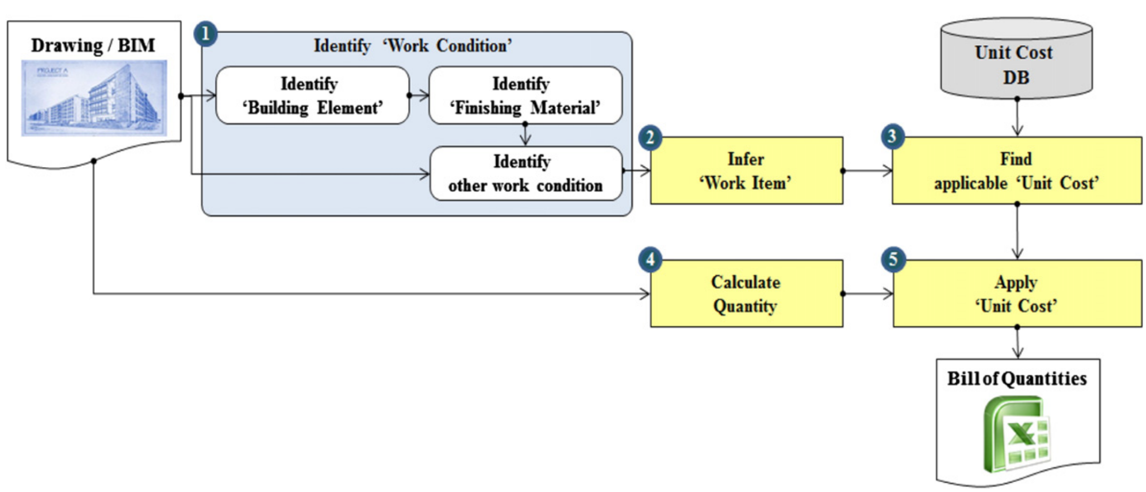


Fig. 1. General process of cost estimation.

Description	Specification	Material		Labor		Equipment		Total	
		Rate	Amount	Rate	Amount	Rate	Amount	Rate	Amount
타일압착붙임.200*200(타일C) 바닥,바탕24mm+압5mm M2 건축 11-2,11-4 (호표 2139)									
			2,138.0		35,989.0		0.0		38,127.0
타일압착붙임.300*300(타일C) 바닥,바탕12mm+압5mm M2 건축 11-2,11-4 (호표 2140)									
			2,068.0		35,120.0		0.0		37,188.0
타일압착붙임.300*300(타일C) 바닥,바탕15mm+압5mm M2 건축 11-2,11-4 (호표 2141)									
			2,068.0		35,337.0		0.0		37,405.0
타일압착붙임.300*300(타일C) 바닥,바탕18mm+압5mm M2 건축 11-2,11-4 (호표 2142)									
A: Work Item			2,068.0		B: Unit Cost		0.0		37,622.0
타일압착붙임.300*300(타일C) 바닥,바탕24mm+압5mm M2 건축 11-2,11-4 (호표 2143)									
			2,068.0		35,989.0		0.0		38,057.0
타일압착붙임.장변108(타일C) 바닥,바탕12mm+압5mm M2 건축 11-2,11-4 (호표 2144)									
			2,569.0		42,860.0		0.0		45,429.0
타일압착붙임.장변108(타일C) 바닥,바탕15mm+압5mm M2 건축 11-2,11-4 (호표 2145)									
			2,569.0		43,077.0		0.0		45,646.0
타일압착붙임.장변108(타일C) 바닥,바탕18mm+압5mm M2 건축 11-2,11-4 (호표 2146)									
			2,569.0		43,294.0		0.0		45,863.0
타일압착붙임.장변108(타일C) 바닥,바탕24mm+압5mm M2 건축 11-2,11-4 (호표 2147)									
			2,569.0		43,657.0		0.0		46,226.0
타일압착붙임.장변227(타일C) 바닥,바탕12mm+압5mm M2 건축 11-2,11-4 (호표 2148)									
			2,394.0		41,348.0		0.0		43,742.0

Fig. 2. Example of unit cost DB.

et al. [2] described the implementation of BIM-based tools to support the activities of the estimating department of a construction company on a large infrastructure project. They complement existing implementation theories in construction management that advocate "technology push" implementations during which existing work processes need to be radically changed to align with the functionality of the BIM-based tools.

In summary, there have been numerous researches on the automation of cost estimation. Some aims for the accuracy improvement of BIM-based quantity take-off, while others propose a term matching methodology for work items having different expressions. Some research suggests the method of property information modeling for cost estimation using rule and semantic databases; however, there have been no studies using BIM data and ontology to automate the selection and matching work items to the elements of buildings and their materials.

2.2. Ontology in construction

Lee [16] proposed an extension to the World Wide Web (WWW) named the Semantic Web, which can handle Web data without human intervention. The Semantic Web allows semantic searches that find more accurate information than the current Web, which makes it easy to share and reuse useful information and corporate knowledge.

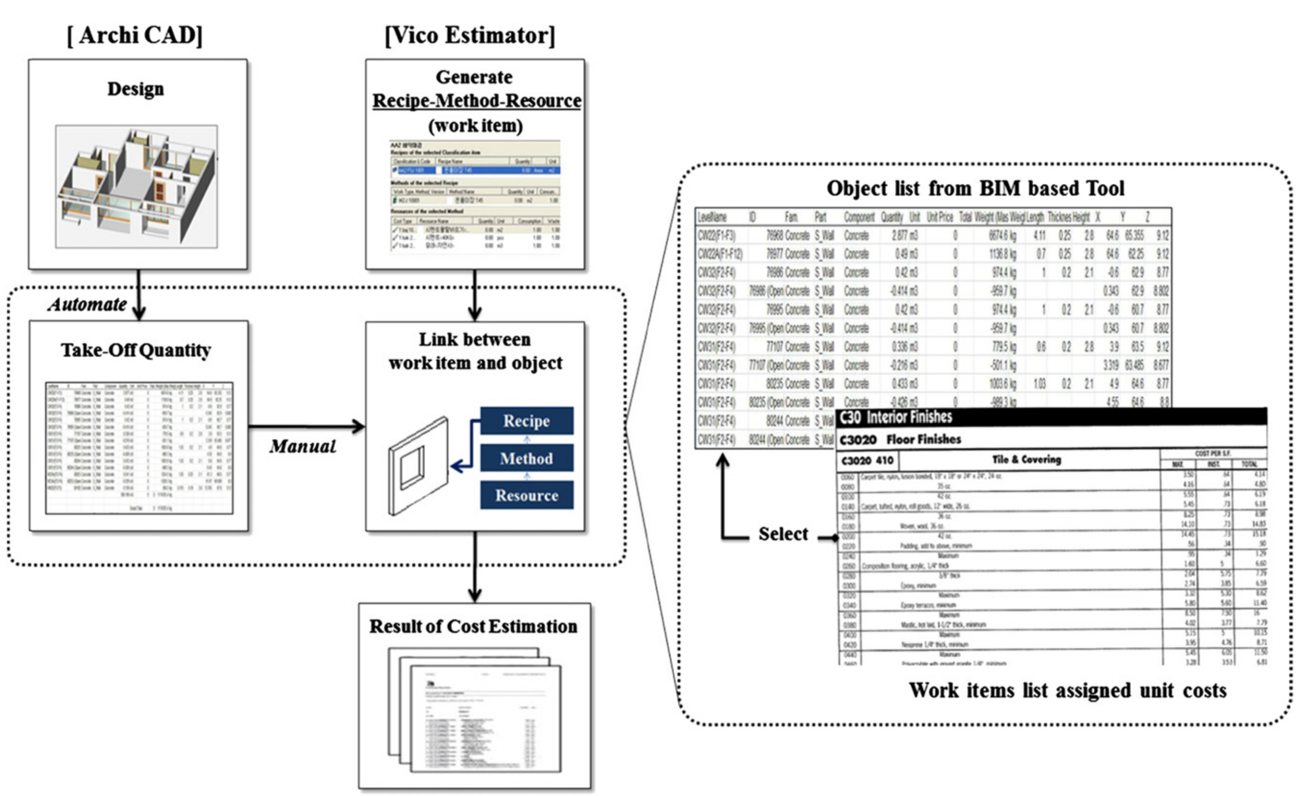


Fig. 3. Cost estimation process by Vico Estimator 2009.

The data of the Semantic Web are expressed in a computer-readable format using ontology—the key technology of the Semantic Web, which is defined as the 'formal and explicit specification of shared conceptualization' [17].

By using ontology, which provides data on various concepts and their relationships, the computer automatically makes it possible to reason about data from different data sources in order to manipulate the relevant data or find new knowledge. Today, ontology is applied to many domains, such as information and communications, medical information, and the internet, and it has been studied using various methodologies.

There have been a several studies the application of ontology to the AEC(Architecture, Engineering, Construction)industry. Charlesraj and Kalidindi [18] proposed an ontology-based knowledge-management framework to improve the performance of construction project managers. In the proposed framework, the target level of the manager's skill, knowledge and competency (SKC) is defined by three ontologies: the ontology of construction projects; the ontology of construction project managers' SKC; and ontology of knowledge management tools. Tserng et al. [19] proposed an ontology-based risk management framework of construction projects through a project life-cycle. The research explores knowledge extraction for effective risk management by establishing project risk ontology. The research findings demonstrate that the ontology-based risk management can be applied to the risk management work flow and increase the effectiveness of project risk management. El-Diraby and Osman [20] proposed an ontology concept to present a philosophically influenced model of infrastructure products that focuses on their functions, roles and semantic attributes to facilitate human representation of their construction knowledge. The developed ontology provided a conceptualization of knowledge in civil infrastructure. Buyko et al. [21] suggest the linking of annotations to specific ontologies of linguistic terminology. They concentrate on the description of the mechanism by means of which such externally provided reference ontologies and concrete annotation types are linked, rather than proposing a direct generation of annotation types from one particular ontology.

In addition to the above-mentioned individual-level research, a few large-scale studies have been conducted. First of all, the standard file format, Industry Foundation Classes (IFC), is intended to enable effective information sharing within the AEC industry using ontologies [22]. Ontologies are structured through classification systems to support effective information exchange. This also affects the construction sector where international standards are frequently used. The e-COGNOS ontology [23] is used to facilitate semantic Web-based knowledge management in the construction field. The main idea behind this ontology can be summarized as follows: a set of actors use a set of resources to produce a set of products following certain processes within a work environment and according to certain conditions. It was developed and implemented through collaboration between researchers and leading European contractors. Additionally, there is the Semantic Web-based Open engineering Platform (SWOP) project in Europe, in which they develop a generic and reusable set of Product Modeling Ontologies (PMO) that can be imported and used by the end-user product ontologies for any parametric/configurable product type [24]. Kristian et al. [25] suggested ontologies to support RFID-based links between virtual models and construction components. The ontologies are reviewed from the perspective of an ontology consumer (e.g., system developer). The ontologies are categorized according to their applicability to the specification of technical services, resources, organizational relations, business processes, and overall frameworks for ontology descriptions and their relations.

In summary, there have been quite a number of studies on ontology in the construction industry over the last decade. Some of them deal with ontologies for product modeling and others are for key concepts in construction. Still others are for conceptualization of the construction knowledge. However, there seem to have been no studies specifically on the creation and utilization of ontology to automatically search for the most appropriate work items for the purposes of cost estimation.

3. Ontology for automatic inference of standard work items

3.1. Concept of automated inferring of work items

The scope of our research is to infer work items based on work conditions (i.e., first and second steps in Fig. 1). That is, this research proposes a mechanism based on knowledge structure that uses ontology to automatically infer most appropriate work items. The work conditions — namely, tiling work, room usage, building elements, finishing thickness and base type — are obtained from drawings. Estimators select a work item that is suitable for the work conditions (e.g., room usage, building elements, finishing thickness and base type) using an inference mechanism that is based upon an expert's knowledge. Accordingly, the result of cost estimation changes depending on who is performing the estimate. On the other hand, if the proposed inference mechanism is used for cost estimation, work items can be automatically inferred, and the inferred work items are consistent (see Fig. 4).

This research is limited to tiling work. Fig. 5 shows the proposed inference process using ontology and BIM corresponding to the first and second steps in Fig. 1. To define work conditions and work items for tiling work, this study referred to the standards of estimates, standard technical specifications, historical data, and publications on construction methods. Work conditions which can be extracted from BIM are defined as room usage, building element, finishing base type, and finishing thickness (input). The work items that can be inferred from the semantic inference engine are defined as tile size, tile thickness, tile type, tiling type, tiling material type, joint width, and joint material type (output).

To automate the inference, this study established a work condition ontology that consists of the determinants used to select work items, a work item ontology that consists of factors defining tiling method, and semantic reasoning rules. This research used Protégé v3.4.4, a Java-based ontology editor, to design a Tiling Work Condition Ontology (TWCO) and a Tiling Work Item Ontology (TWIO). The TWCO is an ontology for recognizing BIM data, which is extracted from IFCXML and converted into RDF format as work conditions. The RDF data contains room usage, building elements, finishing thickness, and base type. The TWIO is used to define the work item. The work items consist of tile size, tile thickness, tile type, tiling method, tiling material type, joint width, and joint material type.

Fig. 6 shows the frameworks of TWCO and TWIO. A continuous line (subclassof) denotes a hierarchical relationship between class and subclass, and a dotted line (objectproperty and datatypeproperty) denotes relationships between classes and relationships between class and data value.

3.2. Definition of class

TWIO contains four classes: *SpecificTileType, TilingMethodType, JointType, TilingMaterialType*, and *TilingWorkItem*. '*Tile*' class contains three sub-classes: *TileTHK, TileSize* and *TileType*. '*Joint*' class contains two subclasses: *JointWidth* and *JointMaterialType*. And '*TilingWorkItem*' class contains semantic reasoning rules, which are defined by combining the other classes of TWIO.

TWCO contains five classes: *RoomUsage, BuildingElement, BaseType, FinishTHK*, and *TilingWorkCondition*. The *TilingWorkCondition* class contains semantic reasoning rules which are defined by combining the other classes of TWCO. The *TilingWorkCondition* class also contains the semantic reasoning rules to connect work items defined by TWIO with work conditions recognized by TWCO. The class of the proposed ontologies is described in Table 1.

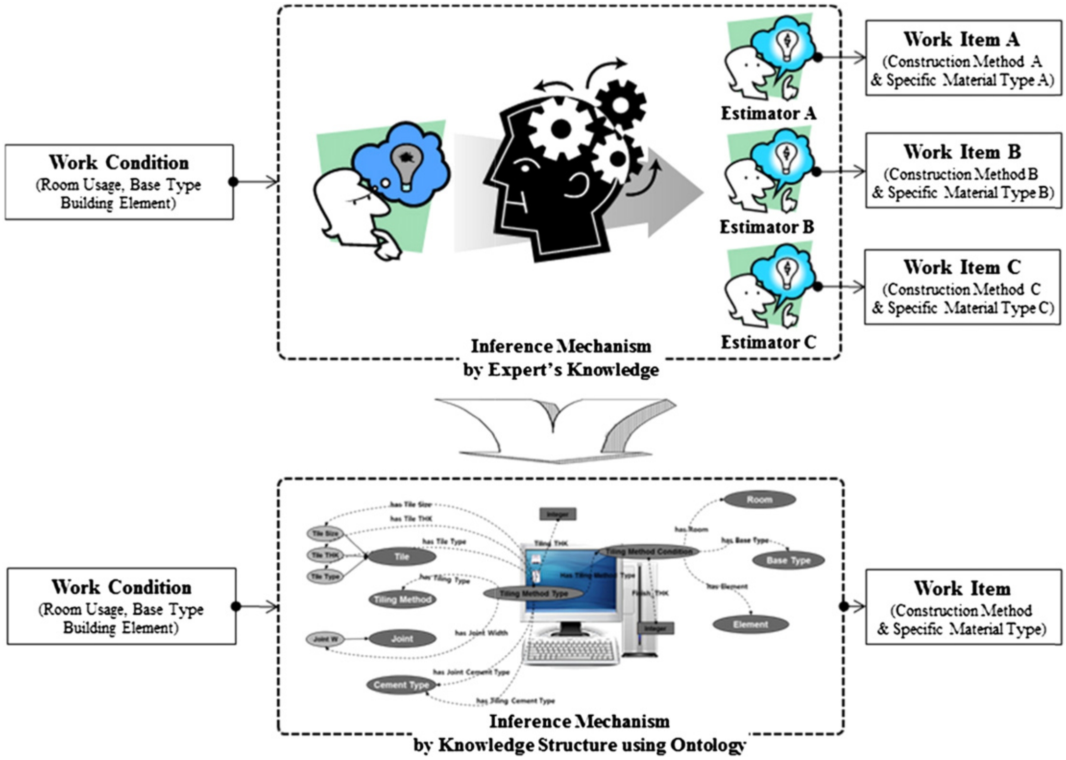


Fig. 4. Inference mechanism using ontology.

3.3. Definition of property

Property of OWL consists of two types: *owl:ObjectProperty* and *owl: DatatypeProperty*. Object property (owl:ObjectProperty) is used to express the relationship between objects. Data type property (owl: DatatypeProperty) is used to express the relationship between object and data values, such as numerical values (i.e., tiling thickness, finishing thickness, and tile thickness). Although tile thickness may vary in data values, the type of tile thickness is usually fixed. Accordingly, tile thickness was defined as an object property. Object properties of the proposed ontologies are described in Table 2.

4. Process for automated inference of standard work item

4.1. Overview

The overall process for the automated inference of work items is described in Fig. 7. Subsequent to the architect's design using the BIM tool, BIM data (e.g., work conditions) are extracted into the IFCXML and converted into the RDF data in a machine-understandable format (see Section 4.2). The reasoning layer creates inferred knowledge such as work items by means of a reasoning process that is based on two ontologies (i.e., TWCO and TWIO) (see Chapter 3) and RDF data of the work

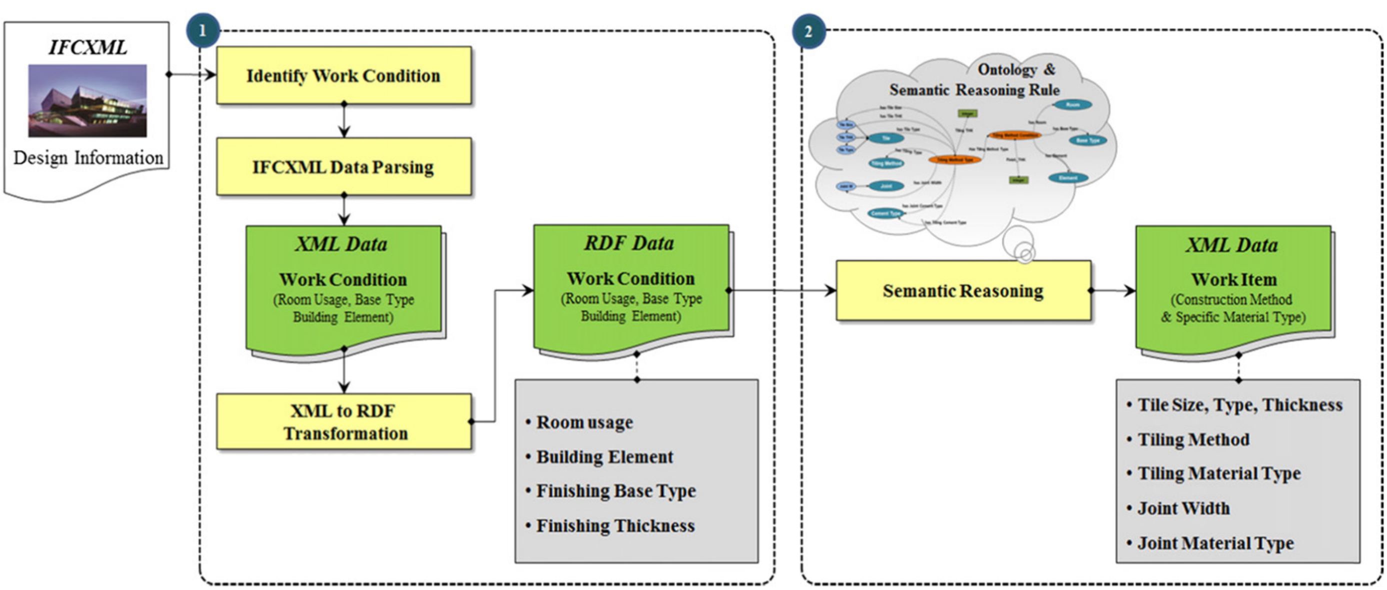


Fig. 5. Data flow for ontological inference process.

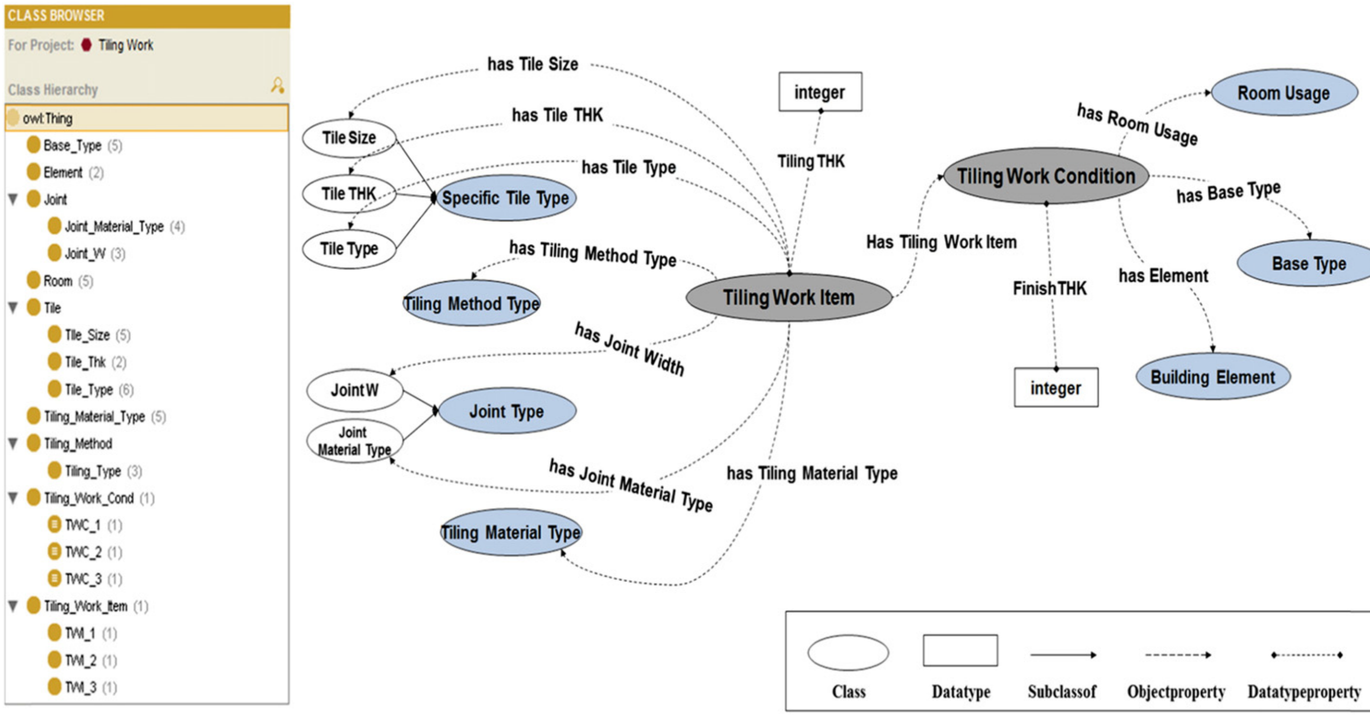


Fig. 6. Framework of TWCO and TWIO.

conditions. Thus, the knowledge base has all of the information about the work item, including tile size, tile thickness, tile type, tiling method, tiling material type, joint width, and joint material type, and work conditions extracted from a building model. Finally, the query engine retrieves relevant information related to the inference of the work item from the knowledge base. In the query layer, Simple Protocol and RDF Query Language (SPARQL) are used to query language in order to define work item queries, and the result of the queries is expressed in XML format (see Section 4.3).

This research also presents a case study that confirms that the proposed ontology and semantic reasoning rule actually work in real-world situations.

Table 1
Definition of classes.

Class		Description and instances
Room usage		Room usage: kitchen, toilet, laundry room, hall, entrance, bath room
Building element		Building element: internal wall, external wall, floor, ceiling
Base type		Finishing base type: ALC, board, concrete, masonry, mortar
Tiling work condition		Work condition of tiling work: the combination of room usage, building element, finishing base type, and finish thickness.
Specific tile Type	*Tile size*	Tile size: 150 × 150, 200 × 200, 200 × 250, 250 × 250, 300 × 300
	Tile THK	Tile thickness: 6 mm, 7 mm
	Tile type	Tile type: ceramic tile, carpet tile, porcelain tile, clinker tile, asphalt tile, glass mosaic tile
Tiling method type		Tiling Method type: tiling type 1, tiling type 2, tiling type 3
Tiling material type		Tiling material type: white cement, ordinary cement, tile cement, white tile cement, tile bond
Joint type	*Joint width*	Joint width: 2 mm, 4 mm, 5 mm
	Joint material type	Joint material type: white cement, ordinary cement, tile cement, white tile cement
Tiling work item		Work item of tiling work: the combination of tile size, tile thickness, tile type, tiling type, tiling material type joint width, and joint material type

4.2. Information extraction from IFCXML and conversion to RDF

To automatically infer the work item, first, BIM data are extracted from IFCXML. Then, the extracted BIM data are converted to RDF data in a machine-understandable format. In this case, tiling work, room usage, building element, finishing base type, finishing thickness were all defined as work conditions that were determinants of the tiling method. IFCXML was analyzed to extract the BIM data.

In order to show the process of automated inference, we first built a sample model of a building using ArchiCAD14 software, which supports 3D-CAD modeling. Then, as shown in Fig. 8, the IFCXML of the sample model was analyzed.

The basic structures of BIM data are based on the IFCXML [26], and the elements and attributes of the IFCXML are derived from the standard IFC. In this research, five main elements were extracted from IFCXML: *Ifcspace, IfcRelSpaceBoundry, Ifcslab/Ifcwall, IfcMaterialLayer,*

Table 2
Definition of properties.

Object property	Description
Has room usage	*Tiling Work Condition* has only one member of the *RoomUsage* class
Has building element	*Tiling Work Condition* has only one member of the *BuildingElement* class
Has base type	*Tiling Work Condition* has only one member of the *BaseType* class
Has tiling work item	*Tiling Work Condition* has only one member of the *TilingMethodType* class
Has tile size	*Tiling Work Item* has only one member of the *TileSize* class
Has tile THK	*Tiling Work Item* has only one member of the *TileTHK* class
Has tile type	*Tiling Work Item* has only one member of the *TileType* class
Has tiling method type	*Tiling Work Item* has only one member of the *TilingMethodType* class
Has tiling material type	*Tiling Work Item* has only one member of the *TilingMaterialType* class
Has joint width	*Tiling Work Item* has only one member of the *JointWidth* class
Has joint material type	*Tiling Work Item* has only one member of the *JointMaterialType* class

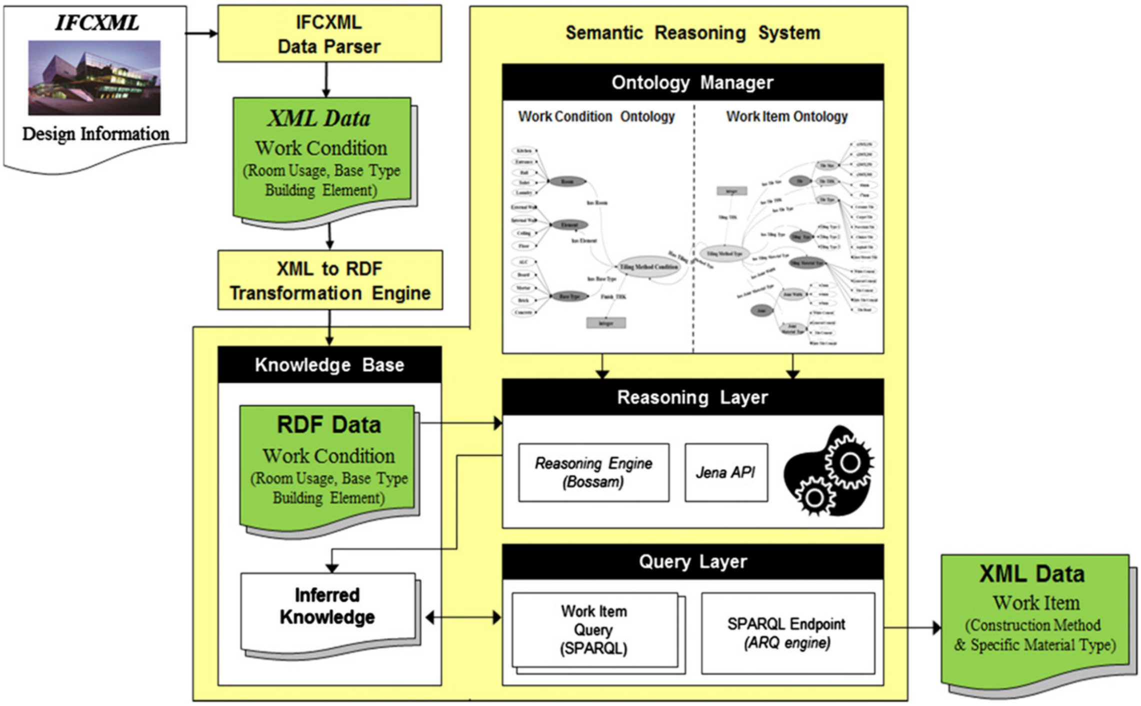


Fig. 7. System architecture of ontological inference.

and *IfcMaterial*. Fig. 8 shows the relationships among these elements; that is, room usage can be extracted from *Ifcspace*, and building elements of its space can be extracted from *Ifcslab* or *Ifcwall* in *IfcRelSpaceBoundry*. Also, finishing thickness can be extracted from *LayerThickness* in *IfcMaterialLayer*, and finishing base type can be extracted from *name* in *IfcMaterial*. In the IFCXML, each room (room usage), element (building element), finishing thickness and finishing base type (base type) corresponds to the *Ifcspace, Ifcslab/Ifcwall, IfcRelSpaceBoundry, IfcMaterialLayer,* and *IfcMaterial* of the IFCXML. The BIM data extracted according to relationships among elements of the IFCXML should be converted to RDF.

The purpose of this research is to generate automated inference of work items. We use ontology based on the assumption that BIM data can be extracted from IFCXML. Therefore, technologically, an extraction and conversion tool should be developed in future research.

4.3. Semantic reasoning and query

4.3.1. Semantic reasoning

The process of semantic reasoning using TWCO and TWIO is shown in Fig. 9. The first step is to recognize the 'work condition': BIM data extracted from IFCXML is recognized as one of the work conditions using TWCO. The second step is to select the 'work item': the most appropriate work item is selected using TWIO.

For example, each 'Kitchen, Wall, Concrete, and 24 mm' is automatically recognized as a sub-class of the 'Room, Element, Base Type, and

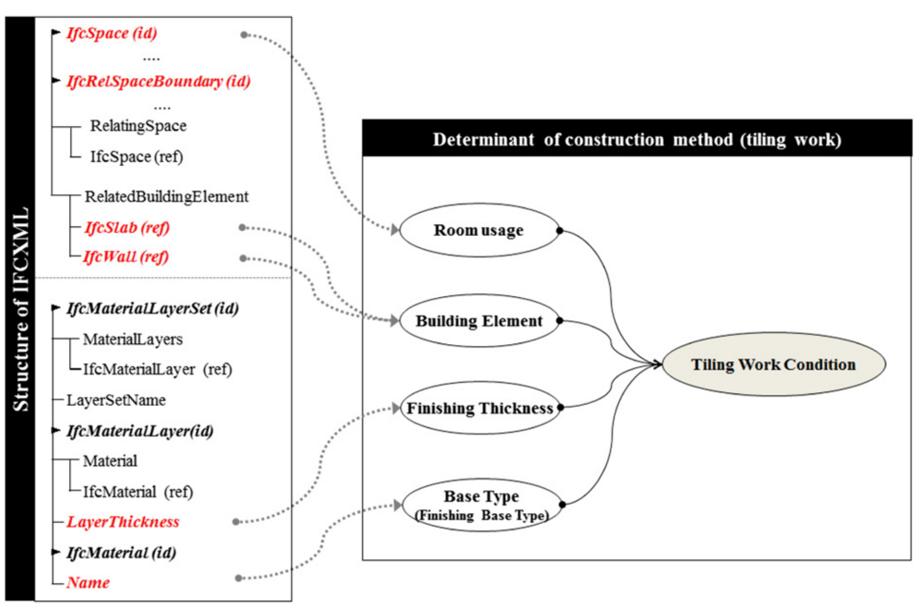


Fig. 8. Relationships among elements of the IFCXML.

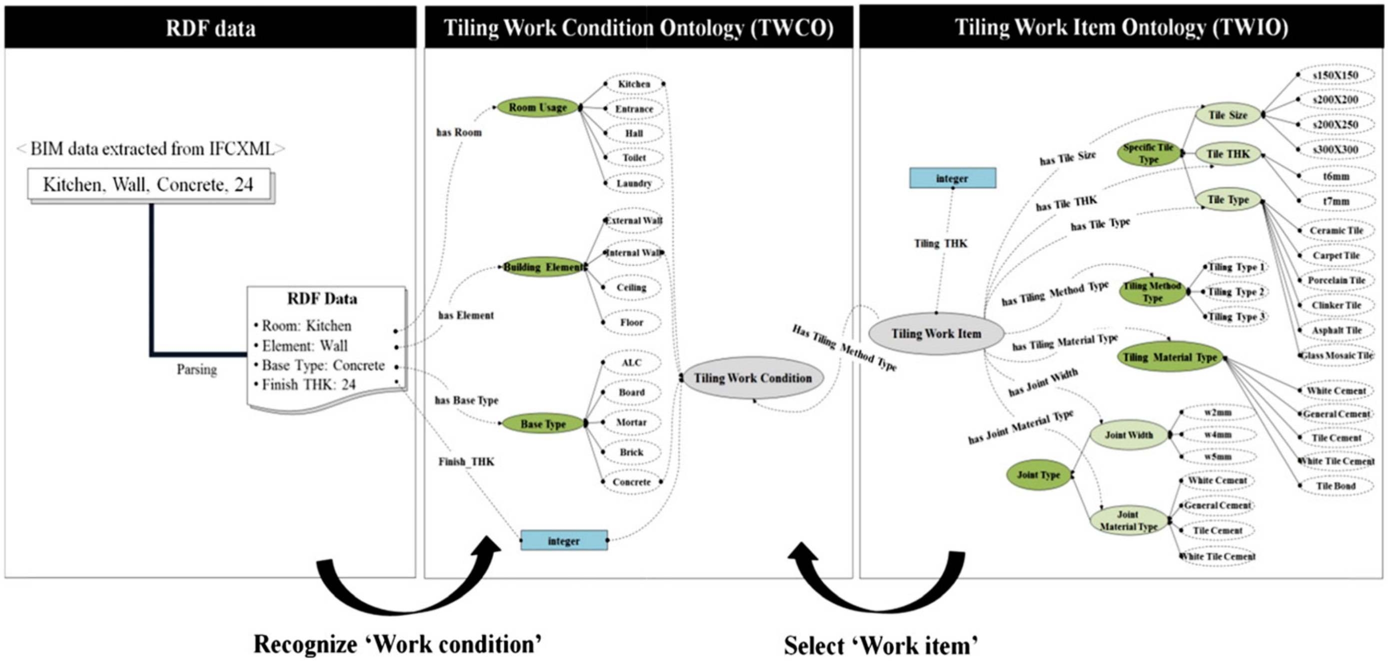


Fig. 9. Semantic reasoning algorithm for tiling work.

Finish THK.' classes. Then, through semantic reasoning, the data is recognized as an instance of 'TWC_1', one of the sub-classes of 'Tiling Work Condition' class, defined as a necessary and sufficient condition with 'room is kitchen, element is wall, base type is concrete, and finish THK. is 24 mm'. Finally, the most appropriate work item is recommended, because the 'TWC_1' class has 'TWI_1', one of the sub-classes of the 'Tiling Work Item' class, defined as necessary condition.

The semantic reasoning rules for the automated inference of work items are as follows.

• **TWC_1 ≡**	• *TWI_1* ≡
- Necessary & Sufficient	- Necessary & Sufficient
∋ hasRoomUsage has *Kitchen*	∋ hasTileSize has *s200 × 200*
∋ hasBuildingElement has *wall*	∋ hasTileType has *CeramicTile*
∋ hasBaseType has *Concrete*	∋ hasTileThk has *6 mm*
∋ hasFinichThk has *24*	∋ hasTilingType has *Tiling Type 1*
- Necessary	∋ hasTilingMaterialType has *Ordinary cement*
∋ hasTilingMethodType has *TWI_1*	∋ hasTilingThk has *15 mm*
	∋ hasJointWidth has *w2mm*
	∋ hasJointMaterialType has *White Cement*

When the RDF data have been stored in the knowledge base, the reasoning engine creates inferred knowledge by reasoning according to two domain ontologies (i.e., TWCO and TWIO) and RDF data, before adding the inferred knowledge into the knowledge base. We used the Bossam reasoner [27], which has a RETE-based rule engine with native support for reasoning over RDF and OWL.

The overall process for creating the inferred knowledge consists of three steps:

Step 1 The reasoning layer binds the two domain ontologies and material RDF data using the Jena API into bound knowledge, which is a simple, non-redundant collection of ontologies and RDF data.
Step 2 The Bossam reasoner takes the bound knowledge and generates inferred knowledge using its sub-reasoners (e.g. the OWL DL reasoner).
Step 3 The knowledge base stores the inferred knowledge.

4.3.2. Query layer

To retrieve the work item that will be used for automated inference, we use SPARQL, which was developed by the W3C RDF Data Access Working Group [28] to define queries for inferring the work item. The SPARQL retrieves the work conditions stored in the knowledge base, which contains a set of knowledge in a triple structure. A SPARQL query is expressed as a list of conditions in a triple structure similar to the structure of knowledge in the knowledge base. To support the Web-based user interface for SPARQL, we developed a SPARQL endpoint based on the ARQ query engine (http://jena.sourceforge.net/ARQ), which supports the SPARQL query language.

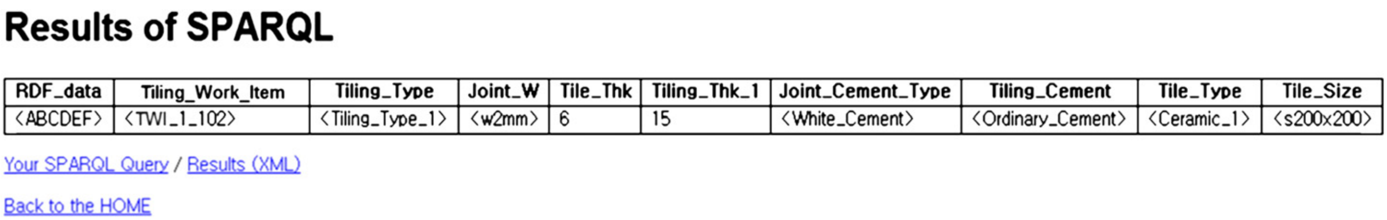
When an expert inputs work item queries as a form of SPARQL via the SPARQL endpoint, the query layer submits them to the ARQ engine, which subsequently retrieves the relevant work item from the knowledge base. Results of the SPARQL queries are returned in XML format (see Fig. 10), which is easy to use in a cost estimating application.

As presented in Fig. 10, the proposed ontologies are well-established relationships between work conditions and work items according to our intention.

4.4. Validation

In this research, we propose an ontological approach that enables the most appropriate work items to be inferred. The proposed approach using BIM data to automate the search for the work items most suitable for building elements and materials. This process can help engineers to find work items more easily and consistently. Using the ontological inference process, if the same BIM data is provided, consistent searching results can be achieved. Also, the ontological inference process provides a methodology to fully automate the estimation of cost. Accordingly, we conducted a case study to demonstrate the proposed ontological inference process in real-world situations. To achieve this, we developed a semantic reasoning system in the system architecture (see Fig. 6) and manually created XML data on work conditions, which were extracted from IFCXML and RDF data on work conditions.

To validate the consistency of the inferred results, we make a comparison between work items that were inferred by the proposed inference mechanism of the ontological knowledge structure and work items inferred by the inference mechanism of expert knowledge. We interviewed five engineers who had on average more than 10 years of experience in South Korea. We provided five engineers with the same work conditions as those defined in this



Results of SPARQL

RDF_data	Tiling_Work_Item	Tiling_Type	Joint_W	Tile_Thk	Tiling_Thk_1	Joint_Cement_Type	Tiling_Cement	Tile_Type	Tile_Size
<ABCDEF>	<TWI_1_102>	<Tiling_Type_1>	<w2mm>	6	15	<White_Cement>	<Ordinary_Cement>	<Ceramic_1>	<s200x200>

Your SPARQL Query / Results (XML)

Back to the HOME

Fig. 10. Results of SPARQL.

research (i.e., room usage — kitchen; building element — wall; finishing base type — concrete; and finishing thickness — 24 mm), and then had engineers choose from among examples (A to D) of components of work items (e.g., tiling method type, tile thickness, tile size, tile type, joint width, joint material type, tiling material type, and tiling thickness) on the basis of given work conditions.

Table 3 shows the results of this comparison. Five engineers selected different components of work items; however, the work items inferred by using the proposed inference mechanism were the same. This result shows that the proposed method provides consistent results. Also, because the ontology should be based on the knowledge of experienced engineers in the future, if the ontology is elaborately defined by the knowledge of experienced engineers, then it will be possible to obtain accurate as well as consistent results. In addition, the proposed process will assist cost estimators to use BIM data more easily and will help the expansion of BIM-based construction management.

5. Conclusions

BIM-based construction management has begun to expand. Since the number of practices that use BIM-based information management has significantly increased, the construction industry has augmented its use of IFC or IFCXML during construction projects; however, although the BIM tool may automatically calculate material quantity, it cannot provide any information on the work items. Theoretically, the information needed for managing construction projects can be automatically obtained from BIM. Practically, however, the information that can be obtained from BIM will remain very limited unless BIM contains full information. Therefore, although BIM tools are used for cost estimation, the intervention of a cost estimator's subjective opinion on appropriate work item cannot be avoided.

Therefore, we propose a methodology to automatically infer the most appropriate work item on the basis of work conditions through the use of semantic technology. Previous research on improving the accuracy of BIM-based quantity take-off, and methodologies have been suggested to match work items that are expressed as different terms; however, the proposed approach emphasizes the use of BIM data to automate the search for work items suitable for building elements and materials. We conduct a comparison between existing estimation methods and the proposed method (see Table 4).

The overall process consists of three steps: First, the BIM data (e.g., work conditions) are extracted into the IFCXML and converted into RDF data, which is a machine-readable format. Second, the reasoning layer creates inferred knowledge that includes work items by means of a reasoning process based on two ontologies (i.e., TWCO and TWIO) and RDF data of the work conditions. Finally, the query engine retrieves relevant information related to the inference of the work item from the knowledge base, and the result of the queries is expressed in the XML format.

Also, we demonstrate that the proposed ontologies and semantic reasoning rules can be utilized in real-world situations, and we validate the consistency of inferred results by comparing inferred work items using proposed inference mechanism by ontological knowledge structure and inferred work items using inference mechanism by expert knowledge. As result of this validation, the ontological inference process is a well-established relationship between work condition and work item according to our intention.

Using the ontology, work conditions are accurately recognized and appropriate work items are automatically inferred without human judgment. The proposed inference process thereby reduces the possibility of several errors caused by the intervention of accurate judgment and improves the efficiency of the tasks. This process contributes full automation of cost estimation and improves the reliability and accuracy of estimation results. In addition, the proposed process will assist cost estimators to use BIM data more easily and will help the expansion of BIM-based construction management.

However, this research has some limitations. The proposed work condition ontology, work item ontology and semantic rules are currently

Table 3
Result of comparison.

Components	Traditional method					Proposed method
	A(8 years)	B(10 years)	C(16 years)	D(8 years)	E(12 years)	
Tiling method type	B	C	C	A	C	A
Tile thickness	A	B	C	C	B	A
Tile size	C	C	D	D	C	B
Tile type	D	B	C	C	B	D
Joint width	A	A	A	A	A	A
Joint material type	D	C	D	D	D	A
Tiling material type	C	C	D	C	C	B
Tiling thickness	A	B	A	C	B	D

1) Tiling Method Type: A. Tiling Type, 1 B. Tiling Type 2, C. Tiling Type 3.
2) Tile Thickness: A. 6 mm, B. 7 mm, C. 11 mm, D. 15 mm.
3) Tile Size: A. 150 × 150, B. 200 × 200, C. 200 × 250, D. 250 × 250.
4) Tile Type: A. Ceramic tile, B. Carpet tile, C. Porcelain tile, D. Clinker tile.
5) Joint Width: A. 2 mm, B. 4 mm, C. 5 mm, D. 9 mm.
6) Joint Material Type: A. White Cement, B. Ordinary Cement, C. Tile Cement, D. White Tile Cement.
7) Tiling Material Type: A. White Cement, B. Ordinary Cement, C. Tile Cement, D. Tile Bond.
8) Tiling Thickness: A. 10 mm, B. 12 mm, C. 13 mm, D. 15 mm.

Table 4
Comparison between existing estimation methods and proposed method.

Estimation methods	General process of cost estimation				
	Identify work condition	Infer work item	Find unit cost	Calculate quantity	Apply unit cost
Conventional cost estimation method	M	M	M	M	M
BIM based cost estimation method	M	M	M	A	A
Proposed cost estimation method (BIM + Ontology)	A	A	A	A	A

A: Automated process by system, M : Manual process by estimator.

limited to tiling work only. Because work conditions differ depending on the type of construction work, ontologies for all aspects of construction work should be developed. Also, because work items differ depending on construction type and technological advancements, the work item ontology should be continually revised and updated. Also, to fully automate the inference process, an IFC data parser and an XML-to-RDF transformation engine should be developed. These limitations should be addressed in future research.

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References

[1] C. Eastman, P. Teicholz, S. Rafael, L. Kathleen, BIM handbook: a guide to building information modeling for owners, managers, designers, engineers, and contractor, John Wiley & Sons, Inc., New Jersey, 2008.
[2] T. Hartmann, H. van Meerveld, N. Vossebeld, A. Adriaanse, Aligning building information model tools and construction management methods, Autom. Constr. (March 22 2012) 605–613.
[3] Innovaya, Innovaya Visual Estimating, http://www.innovaya.com/prod_ve.htm 2010.
[4] Vico, Vico Estimator, http://www.vicosoftware.com/products/vico-estimator-2009/tabid/85114/Default.aspx2010.
[5] Tokmo, Tokmo Production System, http://www.tokmo.com/product.html 2009.
[6] U.S.Cost, Success Design Exchange, http://www.uscost.com/designexchange.asp 2010.
[7] Sage, Success Design Exchange, http://www.sagecre.com/products/timberline_office/estimating/estimating_extended_timberliti_office_estimating_software 2010.
[8] Winest, Winest DesignEst Pro, http://www.winest.com/products/add-ons/designestpro.aspx 2010.
[9] J.H. Ok, M.C. Lee, K.N. Jang, A Study on the Modeling of BIM Property Information in Reflection of the Public Cost Estimate Distinctions, Proceeding of Korea Institute of Construction Engineering and Management, 2009, pp. 772–777.
[10] O.C. Kwon, C.W. Jo, J.W. Cho, Introduction of BIM quality standard for quantity take-off, J. Korea Inst. Build. Constr. 11 (2) (2011) 171–180.
[11] K.J. Koo, J.K. Song, S.C. Park, S.H. Park, A work item matching process model for using historical unit prices, J. Archit. Inst. Korea 24 (6) (2008) 61–68.
[12] S. Staub-French, M. Fischer, J. Kunz, B. Paulson, A generic feature-driven activity-based cost estimation process, Adv. Eng. Inform. 17 (1) (2003) 23–39.
[13] C. Fu, A. Ghassan, M.P. Amanda, A. Lee, S. Wu, IFC implementation in lifecycle costing, J. Harbin Inst. Technol. 11 (4) (2004) 437–441.
[14] Z.L. Ma, X.D. Zhang, S. Wu, Z.H. Wei, Z. Lou, Framework design for BIM-based construction cost estimating software, Proceedings of the CIB W78 2010:27th International Conference, 2010, pp. 1–7.
[15] Z. Ma, Z. Wei, X. Zhang, S. Qiu, P. Wang, Intelligent generation of Bill of Quantity from IFC subject to Chinese standard, Proceedings of the 28th ISARC, 2011, pp. 740–745.
[16] T.B. Lee, J. Hendler, O. Lassila, The semantic web, Scientific American magazineMay 2001.
[17] T. Gruber, A translation approach to portable ontology specification, J. Knowl. Acquis. 5 (2) (1993) 199–200.
[18] V. Charlesraj, S.N. Kalidindi, An ontology-based knowledge management framework for performance improvement of construction project managers, The 23rd international symposium on automation and robotics in construction, 2006, pp. 762–767.
[19] H. Tserng, S. Yin, R. Dzeng, B. Wou, M. Tsai, W. Chen, A study of ontology-based risk management framework of construction projects through project life cycle, J. Autom. Constr. 18 (7) (2009) 994–1008.
[20] T. Ei-Diraby, H. Osman, A domain ontology for construction concepts in urban infrastructure products, Autom. Constr. 20 (8) (2011) 1120–1132.
[21] E. Buyko, C. Chiarcos, A. Lora, Ontology-based interface specifications for a NLP pipeline architecture, Proceedings of the sixth international conference on language resources and evaluation, 2008, pp. 847–854.
[22] IAI, Interoperability and the AEC industry, 1995.
[23] T. Ei-Diraby, B. Fies, C. Lima, An ontology for construction knowledge management, Canadian Society for Civil Engineering - 31st Annual Conference: 2003 Building our Civilization, Montreal, H3H 2R9, Canada, Moncton, NB, Canada, 2003, pp. 1949–1956.
[24] Commonwealth scientific and industrial research organization, Semantic Web-based Open Engineering Platform, Project co-funded by the European Commission within the Sixth Framework Programme (2002–2006), 2005, (STRP NMP2-CT-2005-016972).
[25] B.S. Kristian, C. Per, S. Kjeld, Ontologies to Support RFID-Based Link between Virtual Models and Construction Components, Comput.-Aided Civ. Infrastruct. Eng. 25 (2010) 285–302.
[26] T. Liebich, IFC 2x edition 3, model implementation guide version 2.0, BuildingSMART international modeling support group, 2009.
[27] M. Jang, J. Sohn, Bossam: an extended rule engine for OWL inferencing, Proceedings of Rules and Rule Markup Languages for the Semantic Web, Lecture notes in computer science, 3323, 2004, pp. 128–138.
[28] E. Prud'hommeaux, A. Seaborne, SPARQL query language for RDF, W3C recommendation 15 January, Available at http://www.w3.org/TR/rdf-sparql-query/ 2008.