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A Proposal for Basic Formal Ontology for Knowledge Management in Building Information Modeling Domain

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Abstract: The construction industry produces enormous amounts of information, relying on building information modeling (BIM). However, due to interoperability issues, valuable information is not being used properly. Ontology offers a solution to this interoperability. A complete knowledge base can be provided by reusing basic formal ontology (BFO). In previous studies, domain ontology was developed without BFO. Domain ontology requires loads of effort to reuse because domain ontology is too detailed. To increase the reuse rate and establish a complete knowledge base, it is necessary to develop BFO. This study has developed the BFO in the BIM domain to advance interoperability. First, unnecessary parts were omitted from the existing BFO development process, the process was simplified, and the base of hierarchy was created by extracting the most basic superclasses of the BFO model from Revit, the software of BIM. Based on that hierarchy, each child class was created, and the BFO model was completed by completing the relation of each class. After completion of the model, reliability, in addition to the completeness of the model, was evaluated through a query. Domain experts can reuse the BFO when defining relations between concepts and entities. The proposed BFO will be the foundation of future ontology developments in the BIM domain. This study facilitates future researchers to enhance interoperability in the BIM domain and make the ontology more complete to improve information sharing.

Keywords: basic formal ontology; knowledge management; building information modeling

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1. Introduction

Due to the development of construction technology, the need for information management technology is increasing as the construction industry produces various information and data [1]. Numerous kinds of studies have been performed to assist construction information management [2–5]. However, there are interoperability issues due to the different formats of different systems [6,7]. Also, digitized documents can only be understood by humans. In order to exchange and share useful information between computers and humans, digital documents must be converted into a format that can be understood by a machine or computer system [6]. The construction industry has made efforts to use information technologies to support knowledge sharing in a variety of ways [4]. Many frameworks have been created to address interoperability issues in various areas of configuration. Besides, industry foundation classes (IFC) are continually being developed to overcome shortcomings in information transfer. However, to date, IFC has partially limited the interoperability of information and cannot express many specific conditions clearly. Besides, most proposed frameworks have not been completely validated. Therefore, there are many difficulties in obtaining data from building information modeling (BIM) and IFC-based models [8]. Identifying information requires professionals to invest time and effort in exploring, investigating, and representing information [9,10]. For this reason, a computer-assisted knowledge management system is needed so that experts can put on full information in a particular area [11]. Ontology is a kind of repository that can store knowledge concepts using descriptions and relations and exchange and share knowledge between systems [12]. Domain ontology allows practitioners or soft agents to share their comprehension of information structures. Recently, many efforts have been made to introduce the ontology concept into the construction sector: Construction Industry Ontology (CIO): The CIO project, led by the National Institute of Standards and Technology (NIST), aims to develop a comprehensive ontology for the construction industry. The CIO will provide a standard vocabulary and common framework for representing and sharing knowledge across different domains and stakeholders in the construction sector. Ontology for Sustainable Construction (OSCO): the OSCO project is an initiative to develop an ontology for sustainable construction. The ontology will include concepts related to sustainable building design, construction, and operation, such as energy efficiency, waste reduction, and green materials. Construction Process Ontology (CPO): the CPO project aims to represent the construction process and its various phases, including planning, design, construction, and maintenance. The ontology will provide a common language for representing and sharing knowledge about construction processes, which can help to improve efficiency and reduce errors. BIM Ontology: Building Information Modeling (BIM) is a digital representation of the physical and functional characteristics of a building. The BIM Ontology project aims to develop an ontology for BIM data, which can help to improve data integration and interoperability among different BIM software tools and stakeholders. These initiatives aim to improve collaboration, knowledge sharing, and efficiency in the construction process, ultimately leading to better outcomes for construction projects. However, when building a domain ontology in the construction area, the reuse of the ontology is rarely achieved. There are not enough databases to use for the ontology project. Thus, the current construction ontology database's development is significant for future research. The basic formal ontology is of paramount importance as the knowledge base is the foundation of ontology-related projects in the construction area. Most knowledge-sharing schemes related to ontology should begin working with a basic formal ontology model [13,14]. Several previous studies have been done on ontology modeling according to the needs of each field. However, previously developed ontologies are too detailed for reuse because they were written directly as domain models without basic formal ontology. Therefore, it can be partially reused but requires a lot of effort and time to understand and requires much modification. In other words, it might be more efficient to start new domain modeling. While there are benefits to developing ontologies for specific domains, such as the construction sector, it is important to consider the existing ontologies and their potential for reuse or adaptation. Starting a new ontology from scratch can be time-consuming and resource-intensive, especially if there are already ontologies that can be leveraged for the domain. However, in some cases, it may be necessary to start a new ontology if the existing ontologies are inadequate for the specific needs of the domain or if the domain is highly specialized and requires a unique ontology. In these cases, starting a new ontology may be more efficient than trying to adapt an existing ontology. Overall, the decision to start a new ontology or use an existing one would depend on the specific needs and context of the domain in question. A thorough analysis of the existing ontologies and their potential for reuse or adaptation would need to be conducted to determine the most efficient and effective approach. Therefore, this study aimed to increase reusability by developing a basic formal ontology that can be supported when developing a domain model, based on the structure of the BIM platform, with simple essential elements (see Figure 1). In addition, in the field of construction, it is rare to perform basic formal ontology modeling by reusing an existing model, so this study is the first partial development of the previously developed basic formal ontology.

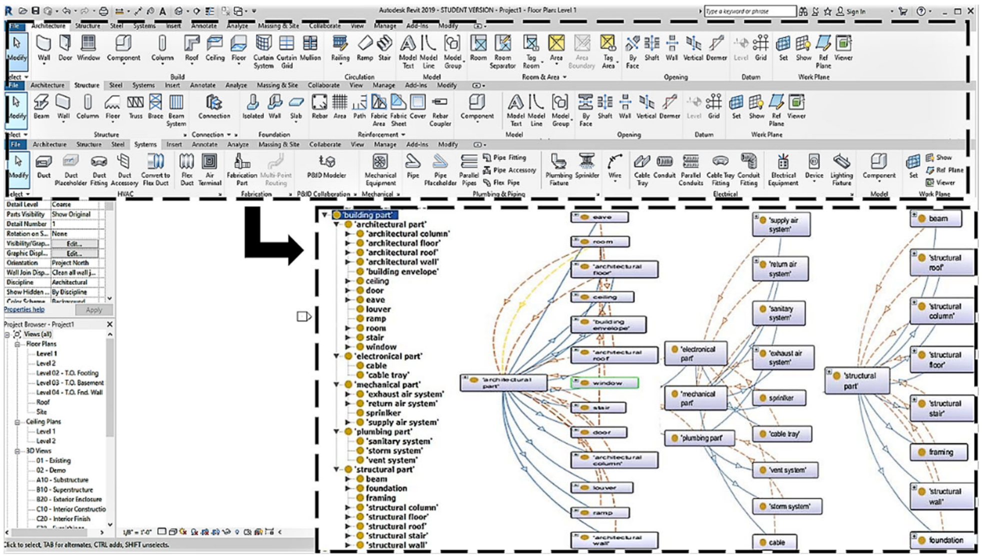

Figure 1. Basic formal ontology based on the structure of BIM.

2. Background Knowledge

2.1. Ontology

Ontology is an effective method to enable information sharing and recycling. Ontologies provide a structured and formalized representation of knowledge that can facilitate the sharing and reuse of information across different systems and applications. There is a significant body of literature and research that supports the use of ontologies for information sharing and recycling in various domains, including but not limited to biomedical informatics, e-commerce, and the semantic web. In fact, ontologies have become a fundamental component of many knowledge-based systems, such as expert systems and decision support systems. Ontologies implement concepts and groups of connections within a specific domain (see Figure 2). Protégé is generally utilized as an ontology editor to implement a process for scheming and executing domain ontology. Many domains create their ontology for various goals. For example, the e-COGNOS project developed an ontology based on IFC and civil engineering standards in the civil engineering area. Ontology engineering is advantageously applied to information sharing and knowledge encoding [6]. Ontologies can be a potential tool for solving interoperability problems. Ontology has an excellent conceptual hierarchy and supports logical reasoning. The exact meaning of the concept is obtained using strict definitions and the relationship between them [15,16]. Ontology demonstrates common identifiable and shareable knowledge and provides knowledge sharing and reuse across knowledge layers. There are four basics of ontology modeling. Four fundamentals are required for all ontology models. First, the concept of representing what a class is described by its name. Second, it is a relationship that represents the connection between existing concepts and instances. Third, axioms present the constraints of concepts and cases. Fourth, an instance representing a specific individual in the class. The most important part of the domain ontology is the class level, which is an essential glossary that supports a reasoning base for accurate thinking. A reasonable class hierarchy is essential to improve the efficiency and accuracy of information retrieval [9]. In conclusion, ontology assists in storing knowledge concepts through descriptions and relations and exchanges and shares knowledge between systems. Besides, domain ontology allows practitioners or soft agents to share their understanding of information structures [6,17].

Figure 2. Implementation concept of the ontology [18].

2.2. Protégé

Protégé is an open-source tool for terminology and ontology editing and management [19]. Protégé applies to all domains and platforms and is used to implement terminology and ontology and knowledge base of a wide range of application domains. For more proper research and applications, Protégé provides a user-friendly interface and is similar to the Windows application style. Protégé was initially used to implement the ontology of the life sciences field, but its application fields are increasing, such as those used to manage the intelligent information resources of enterprises and organizations. Protégé uses the concepts of Individual, Property, and class to model objects. An individual represents an object in the domain and generally means an instance of the class. Property refers to the relationship that these individuals have. That is, it serves to connect two individuals. Class is a kind of group that includes individuals and consists of a superclass and a subclass. Classes are usually expressed by specifying concepts [19]. Protégé provides an application program interface (API) as well as tools for graphical user interfaces (GUIs). Users can also build ontology through Java programming using the API. Moreover, because there are various plug-ins in Protégé, it is widely used by ontology researchers. Protégé supports multiple inheritances and new data consistency checks and has robust scalability [19].

2.3. OntoGraf

OntoGraf is a plug-in for Protégé, an ontology visualization tool [20]. OntoGraf expresses Class and Individual as nodes, and their relationship is expressed as edges. OntoGraf provides automatic layouts such as Grid, Radial, Spring, and Tree. Moreover, the user can arbitrarily locate all nodes. Nodes and edges can be filtered to visualize only the edge types and nodes that the user wants. Furthermore, OntoGraf Nodes can be made invisible. Finally, the user can save the graph in the format of a bitmap image or save the graph to a file and load it later. The visualization tool was created by adding several functions to effectively visualize augmented ontology based on OntoGraf [20].

3. Literature Review

With the development of information technology, information and data are provided through computers and the Internet, but the vast amount of them adds to the effort and time it takes for people to select and use necessary materials and services. Semantic Web technology is the technology that enables computers to perform these tasks by allowing computers to understand the terms of web documents. For example, in the medical science domain, when a patient's symptoms are input into a computer connected to an intelligent web, it is possible to fully automate the expression of the exact disease name and prescription. To this end, in order to allow the computer to recognize the meaning of the knowledge in the web document, it is necessary to build a database that aggregates the relationship between terms such as synonyms, antonyms, and inclusion relations. This is called ontology. Ontology can be used in various fields, such as building information modeling, intelligent services for intelligent robotic systems, intelligent e-business, medical informatization, and bioinformatics, as well as the semantic web. This study reviewed the relevant papers to recognize the study subject and trends related to ontology. Interest in oncology research has been shown to continue to increase. The published ontology studies gradually increased. More studies can be expected as the number of studies increases over time. As the complexity of the project increases and the dependence on information and communication technologies increases, the issues of knowledge interoperability and valid knowledge retrieval approaches will be significant in the use of information and communication technologies. The ontology method is likely to meet needs. Most of the existing research has focused on analyzing ontology architecture concepts and compositional domain ontology for model exchange. There is still a lack of domain ontology that represents construction knowledge and enables interaction between the ontology and the BIM. Domain ontology modeling representing construction knowledge must be performed first, and ontology must be connected to BIM. In the construction sector, the value of information is increasing. Therefore, in order to utilize useful information properly, interoperability is an important topic in construction knowledge management [9]. The researcher must continue to work on ontology studies in the construction sector. In the construction domain, several studies have been conducted to deal with interoperability problems in a variety of approaches and ranges. In view of knowledge arrangements, natural language processing (NLP) technology has been utilized to enucleate information from regulatory text. Chi et al. [21] applied ontology-based text classification (TC) to apply a safety plan by matching job hazard analyses identified in existing resources with hazardous situations. Elghamrawy et al. [22] put forward an automated information retrieval scheme that can explore and deliver comparable incidents. The search method derives the BIM objects and combines them with the project management information system to create a set of queries. Chi et al. [21] offered a tactic based on text classification to care job hazard analysis (JHA) automation. Zhang and El-Gohary [23] discovered the effect of using the syntax and semantics of text to automatically retrieve regulatory information from building code using an automated information extraction (IE) method. Aziz et al. [15] discussed a prototype application for context-aware information transfer using a semantic-based resource description framework schema. Moreover, Wang et al. [24] developed an innovative method to help the management of construction information in context. Weng et al. [25] found that ontology has been shown to support knowledge or information classification systems that are useful for knowledge exchange. Rezgui [26], Elghamrawy and Boukamp [6], and Elghamrawy et al. [22] developed search techniques, and EI-Diraby and Zhang [16] and Niu and Issa [27] performed taxonomy development. Yuchyyshyna et al. [28] proposed an ontological approach to conformity verification, and Lin et al. [29] developed the concept of extraction to confirm the relevance, accuracy, and completeness of the information. In 2012, Benevolenskiy [30] presented an ontology-based model combined with a process-based model to standardize various simulation tasks. Dibley studied the ontology framework for sensor-based building monitoring. In 2016, Zhou and El-Gohary [31] developed an ontology-based text classification algorithm to improve classification performance using the semantics of text. Then in 2017, Zhou and El-Gohary [32] developed an ontology-based information extraction algorithm.

By using structured data, creating domain ontologies based on information-rich BIM improves information sharing and reuse. Semantic selection and data standards have been the subject of numerous investigations. In a BIM setting, Shen et al. [7] built an ontology-based construction monitoring system for prefabricated buildings. Through plug-in integration, the ontology technology was applied to the Revit software to share, reuse, and gather safety risk management expertise in the building of prefabricated structures. An OWL ontology for IFC (ifcOWL) was derived by Pauwels et al. [33] from the IFC EXPRESS schemas. In their research, an EXPRESS-to-OWL converter was built. A safety ontology matched with IFC was created by Farghaly et al. [34], who also created a semantic mapping method between the ontology and ifcOWL. Suter et al. [5] designed various space views for schematic building design using space ontology and layout transformation techniques. The BIM authoring system's room-based building data was semi-automatically transformed into a multi-view spatial model using this technique. The benefit of ontology is that it offers a standard framework for building data networks. In order to effectively promote interoperability without misunderstanding and prevent data loss across different machines, information-rich BIM and ontology can be combined.

Although implicit factual knowledge is objectively present in a BIM context, it cannot be immediately collected and used. As a result, there is little information exchange between the contexts. Contextual data can be retrieved from the BIM environment to create a knowledge management ontology and make up for the absence of semantic logical linkages in BIM. According to [2,11,13,14], the internal structure of knowledge management is determined by the characteristics, while the outward framework of knowledge management is defined by the class hierarchy in the ontology. An ontological approach to integrating operation and maintenance data in BIM for road infrastructure was proposed by Ait-Lamallam et al. [2]. It ensured the sustainability of the road infrastructure and integrated operating and maintenance information within the IFC schema. For the purpose of information retrieval and reasoning in value-for-money analyses, Ren et al. [14] aligned BIM and ontology. The goal of this plan was to facilitate decision-making by obtaining data from a BIM environment with an ontology knowledge base to strengthen the project and financial management methods. A rule-based ontology system was created by Martino et al. [13] that drew conclusions from ontologies derived from the IFC schema. Starting with BIM, this technique identified real estate units and the location of their use. By connecting security concerns to processing through various risk scenarios, Collinge et al. [11]'s BIM-based construction safety risk library promoted implicit and explicit knowledge sharing in a BIM environment.

It Is now common practice to develop BIM application programs with inference assistance for performance analysis and calculations using BIM data in accordance with requirements in laws or standards [35]. With the goal of facilitating intelligent green building evaluation, Jiang et al. [3] introduced a novel strategy that merged BIM and ontology. For automated safety inspections in subway construction, Li et al.'s [36] semantic BIM technique was suggested. The use of SPARQL-based reasoning allowed the integration of heterogeneous data in a BIM context and enabled automatic safety testing. A BIM-based automated code compliance testing methodology that uses ontology was created by Jiang et al. [20] and used a gray-box checking technique. With the help of regulatory papers, this approach helps with code compliance by spotting subpar designs and enhancing design correctness prior to construction. Using a method developed by Zhang et al. [23], building plans created using BIM can be automatically checked to see if they adhere to all applicable codes and laws. This approach used a transformer-based language model to learn semantic representations of data from BIM and regulatory documents merging automated IFC regulatory data.

As mentioned above, various research has been performed in the area of knowledge management to utilize construction knowledge. Several systems, applications, frameworks, and mechanisms have been advanced to date. However, due to the variety of projects and the participation of many experts, the proposed studies did not adapt properly. To take full advantage of the proposed framework, studies must first fine-tune the knowledge-sharing system. Some of them require more testing, verification, and development to improve the system. Above all, to strengthen knowledge management, domain model development must be done first.

4. Methods

As can be seen in Figure 3, the basic formal ontology modeling in this study is basically performed using the hybrid version of the ontology development approach. A hybrid approach to ontology development typically involves combining different methods or techniques, such as a top-down approach with a bottom-up approach, to create an ontology that is both comprehensive and flexible enough to address a wide range of requirements and use cases. Hybrid approaches have several advantages, including first, the need to balance the advantages and disadvantages of different ontology development methods. Second, the desire to leverage existing domain-specific ontologies or external knowledge resources. Third, the need to incorporate input and feedback from various stakeholders and experts. Firth, the goal of creating an ontology that is both comprehensive and easy to maintain and update. Fifth, the need to accommodate different types of data and knowledge sources. A detailed description of each step is given in each section below.

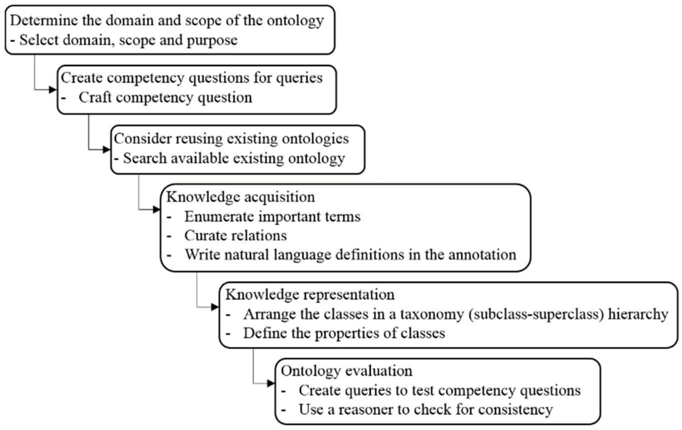

Figure 3. A hybrid version of the ontology development approach.

4.1. Determine the Domain and Scope of the Ontology

Domain ontology is the groundwork of information technology. Normalization of domain ontology provides an outstanding method for interoperable information systems [9]. The domain ontology is applied to deliver a shared representation of concepts within the domain of knowledge [1]. This research creates a domain ontology in the BIM domain through a hybrid ontology modeling process. Although the importance of sharing knowledge about BIM is increasing, domain ontology research on this topic has not been actively conducted, and more study on sharing knowledge about BIM is needed. This study developed a domain ontology with an emphasis on the BIM domain.

4.2. Create Competency Questions for Queries

One method to limit the range of an ontology is to make a list of questions that a knowledge base on ontology should be able to respond to competently [6]. These questions will later be used to verify the domain ontology. Ontologies should cover sufficient information to respond to competency questions. These competency questions are just an outline and do not need to be in-depth [6]. Some of the possible competency questions for basic formal ontology in the BIM domain are shown in Table 1.

Table 1. Conversion competency questions to formalized questions for querying.

Competency Questions	Formalized Questions
Which building parts contain mechanical parts?	'has part' some 'mechanical parts'
Which building parts contain wood?	'composed primarily of some wood
What are the kinds of structural floors?	'part of' some 'structural floor'

4.3. Reusing Existing Ontologies

It has value in taking into consideration what somebody has completed and examining if it can refine and reuse existing domain ontology for a specific domain and work. Reusing the available ontology can be a prerequisite if the research needs to cooperate with a particular ontology or other application already dedicated to the extracted class. Various ontologies are surely accessible in a usable format and can be imported into an environment for ontology development. As many information representation systems can import and export ontology, the format representing the ontology is typically not important. Converting ontology from 1 model to another is not typically complicated if the information representation method cannot operate explicitly in a different format. Libraries of generic ontologies are accessible on the web and in the literature. For instance, domain experts can use the ontology library (http://www.ksl.stanford.edu/software/ontolingua/, accessed on 5 April 2023) or the digital asset modeling language (DAML) ontology library (http://www.daml.org/ontologies/, accessed on5 April 2023). There are also several openly usable infomercial ontologies (e.g., UNSPSC (www.unspsc.org, accessed on 5 April 2023), RosettaNet (www.rosettanet.org, accessed on 5 April 2023), DMOZ (www.dmoz.org, accessed on 5 April 2023), and Ontobee (http://www.ontobee.org/ontology/ENVO, accessed on 5 April 2023). In this study, the ontology model about building parts was found from the Ontobee (See Figure 4) and reused as a part of the domain ontology. As mentioned earlier, there is no platform for sharing domain ontology in the AEC field, so there are many difficulties in finding a reusable domain. For reuse in this study, the building parts found on Ontobee were used partially. Since it is an ontology about building parts made in other fields, it required many modifications in concept and many ways. However, in order to show the reusability, some of the modified class was reused.

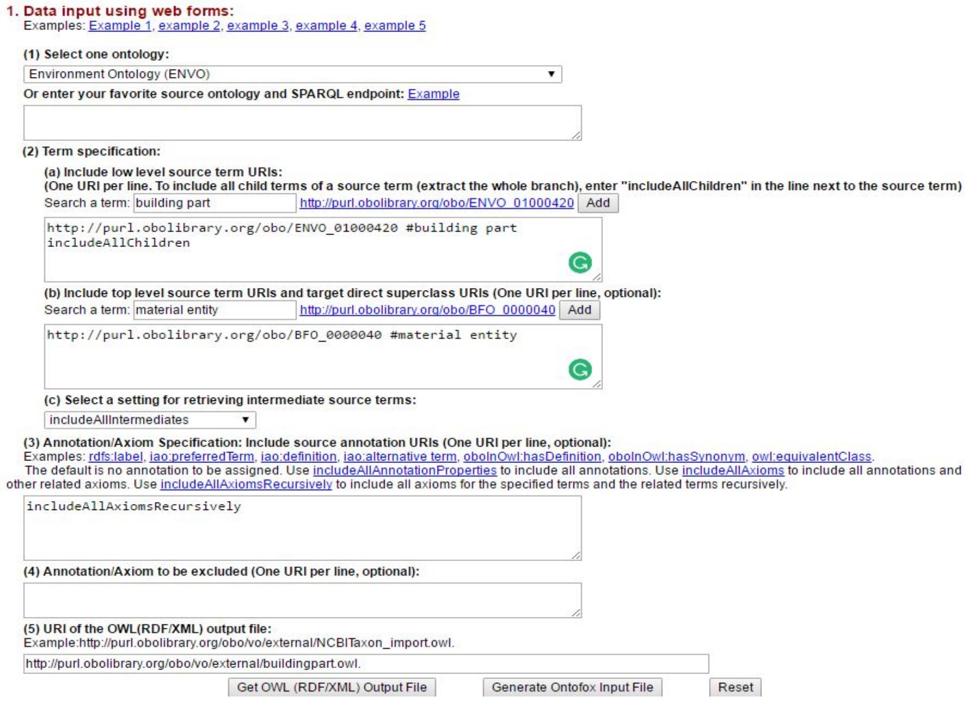

Figure 4. Data input and process to find the appropriate reusable basic formal ontology in Ontobee.

4.4. Identify Essential Terms in the Ontology

First, it is valuable to make a list of all terms related to the specific domain. The developer wants to explain or understand something in the specific domain to the user. It is crucial to have a comprehensive list of terms without considering the definitions that they represent, the relationships between terms, the properties or concepts that can exist, and whether it is a class. The next steps to develop a class hierarchy and define the properties of a concept are closely related. It is challenging to serve 1 of the tasks in ontology modeling, then the other. In general, developers create some definitions of concepts in a hierarchical structure and then continue to describe the properties of these concepts. These steps are essential steps in the ontology-building method. Developers briefly describe here and discuss more complex issues, common pitfalls, and decisions to consider in the next section.

4.5. Create Natural Language Definitions for Each Class in Ontology

Ontologies are increasingly used to promote the reusability of scientific information by allowing disparate data to be integrated under common standardized representations. Definition plays an important role in the use of ontology in both humans and computers. Class definitions allow oncologists and data curators to understand the intended meaning of ontology terms and consistently use these terms in context. The logical definition allows the machine to make inferences that facilitate knowledge discovery by examining the integrity of the ontology and the reason for the annotated data in ontology terms. Therefore, it is important not only to include several types of definitions in ontology in both formal and natural language but also to make these definitions useful by meeting quality standards. Ontology editing tools like Protégé can help to write well-formed logical definitions, but writing useful definitions in natural language is still a problem supported by human ingenuity by a few general principles. Definition authors are often left to their understanding because there are no more accurate instructions [35]. This study has written the definition of each class according to a set of principles and rules that support the creation, editing, and verification of definitions using the existing principles of writing and the definition of dictionaries, terminology, and logic in the ontology community. The definitions developed for this study follow the guidelines for writing definitions in ontologies.

4.6. Define the Classes and the Hierarchy

Generally, there are 3 ways to develop a hierarchy of classes [37]. First, the top-down building method begins with the definition and subsequent conceptualization of the most common concepts in the domain conceptualization. Second, the bottom-up building method groups these classes into more basic concepts, starting with the definition of the most specific classes in the hierarchy [38]. Third, the combination building method is a combination of a top-down and bottom-up approach. Developers describe more prominent concepts first, then simplify and particulate accordingly. None of these 3 approaches is inherently better than the others. The method depends significantly on the domain's personal perspective. If you have a deep understanding of the domain's systematic top-down development process, it can be fit to use a top-down method. The combination method is a suitable way for most ontology developers because the middle concept tends to be more descriptive in the domain [29]. A top-down approach may be more effective if developers think of things by first distinguishing the most common classifications. The bottom-up method can be more suitable if the developer begins with a specific example [39]. Whatever method is chosen, developers usually start by defining a class. First, the developer chooses a term that refers to an object with independent existence, not a term to describe these objects. This term will be a class in ontology and an anchor in the class hierarchy. Developers make arrangements for classes into a hierarchical classification scheme by definition, whether an instance object of 1 class is necessarily an instance of another class.

4.7. Define the Properties of Classes

Classes alone cannot deliver sufficient information to respond to competency questions. When a developer defines part of a class, the developer needs to explain the internal conceptual structure. The class has been selected from a list of terms already created by the developer. Most of the remaining terms can be properties of these classes. For each property in the list, the developer needs to decide which class to describe.

4.8. Development and Validation

This research developed and validated the basic formal ontology model in the following steps. (1) In building information modeling, this study identified the functions and uses, as well as the parts of the building that make up the building most commonly. (2) Classes identified are categorized by function and purpose. (3) In ontology, this study has written a new class definition for building components. (4) This study has created a description and logic of classes representing the functions and uses of building parts. (5) In order to verify the ontology, this study conducted a logical query test with the competency question and conducted a consistency check through Protégé's built-in reasoning tool. This study developed an ontology by using Protégé. This study screened and limited new terms and classes from the Revit software and Revit library since Revit software is a commonly-used software for building information modeling. Also, Revit software cannot contain all of the building parts, so when we need to use some building part which is not in the Revit software, we need to import some building parts from the Revit library. This study reused some classes of environmental ontology for building parts. All the classes developed in this study were defined and modified accordingly regarding Termium Plus, Merriam Webster, Wikipedia, and selected construction handbooks. All definitions have been amended according to ontology definition rules. The ontology of these developed building parts has been verified through queries under the formalized competency questions.

5. Results and Discussion

5.1. The Basic Formal Ontology Model

The developed basic formal ontology model has a total of 114 classes. Thirty of them utilized classes from the environmental ontology and 84 new classes have been added based on the Revit and Revit libraries. There are also four types of relationships (is a, part of, has a part, composed primarily of). These four relationships were created to connect classes according to description logic, and each class was applied to connect as needed. For the class annotation, each class covers at least four annotations such as definition, definition source, term editor, language, comments, and reference. Figure 5 shows the annotations and description logic. In this study, the developed model partially uses the existing model, so there are superclasses of the building part. Existing superclasses can also be modified, but this model has kept them to show reusability. In the annotation, language can be selected depending on the user preference, display definitions, comments, and if classes can be reused. It also shows where the class is imported from. Figure 6 shows the structure of the significant class of the proposed basic formal ontology model. Since this model is based on BIM, the structure of the BIM software is used as it is. It is divided into five classes, such as architecture, structure, electricity, machinery, and plumbing. Figure 7 shows the multiple subclasses of the main five classes. Although not shown in the figure, other subclasses exist as needed. Each box shown in Figures 6 and 7 with OntoGraph represents classes, and the lines connecting the boxes represent the relationship, and the relationship can be classified according to the color and shape of the line. The proposed basic formal ontology model is a cornerstone of developing application systems for building information modeling by using information and data. The purpose of the development of this domain ontology is that BIM is used for construction automation and information and research, such as artificial intelligence, because it generates a lot of knowledge and information data. Therefore, in order to prepare the base for the knowledge system of BIM-based research, it is recommended to reuse the proposed domain ontology by developing a perfect domain ontology. The developed basic formal ontology model covers building element information, such as that regarding columns, slabs, walls, and so on, based on BIM and delivers the basic interface for linking the ontology and a BIM platform.

5.2. Query Results

Several competency questions were made to verify the proposed basic formal ontology model, and the competency questions were formalized to query it. For example, the competency question (which building parts contain wood?) was formalized ('has part' some wood) to query the developed basic formal ontology model on the system, and the expected result (expected query result: 'has part' some wood—wooden beam, wooden columns, wooden doors, wooden exterior walls, wooden floors, wooden frame windows, wooden interior walls, wooden stairs, and wooden building roof) was created and compared with the actual result to verify the accuracy of the result before obtaining the actual result. As can be seen in Figure 8, the results of the query matched the expected results. In addition to the results shown in Figure 8, several more queries were performed, and the test results were consistent with the expected results, so the domain model proposed in this study was verified for reliability.

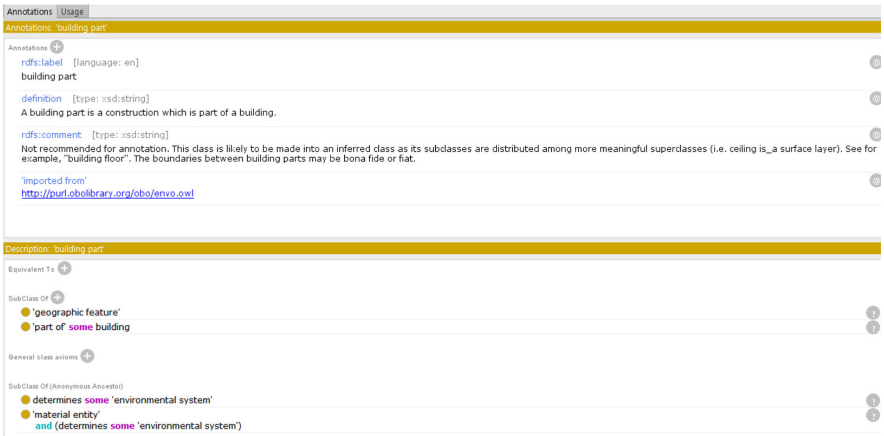

Figure 5. Annotations and description logic.

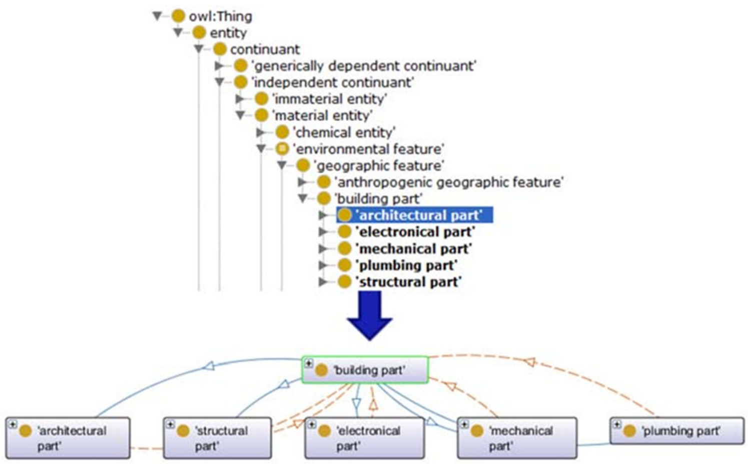

Figure 6. Subclass hierarchy of the basic formal ontology with OntoGraf.

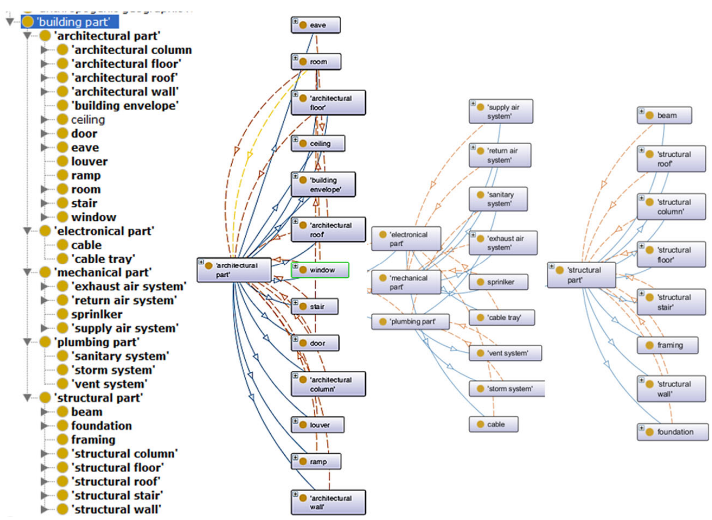

Figure 7. 2nd subclass hierarchy of the basic formal ontology with OntoGraf.

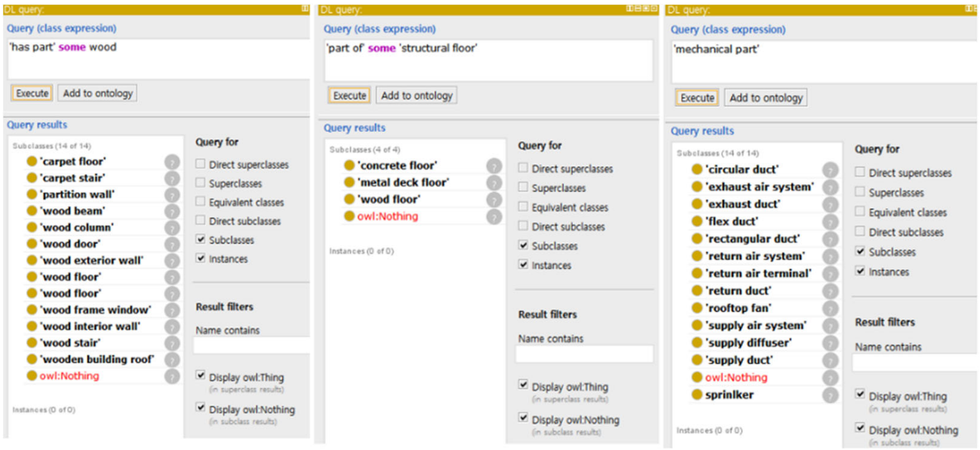

Figure 8. Description logic query results.

5.3. Discussion

This study develops a basic formal ontology to establish the knowledge base for building the information modeling domain. This developed basic formal ontology model will be used as a knowledge base for the development of an automatic building safety analysis system at the design stage through BIM platforms. In addition, domain ontology development can be partially corrected, supplemented, and reused, making it easier for domain experts to access domain ontology creation and contributing to the development of an improved knowledge system. This study is also based on the BIM platform to be applicable to BIM-related applications. Therefore, the proposed ontology will be the basis for future research in the BIM domain. However, there were some limitations that need to be addressed in future studies. First, this study attempted to reuse the domain ontology developed in the BIM domain. However, finding reusable ontology information related to the construction area was difficult because, in the construction field, ontology sharing was not achieved due to the absence of a sharing platform. So, in the environmental domain, which is not in the construction-related domain, building parts were found and partially used. Secondly, there is considerable software for building information modeling, and it is in a different format. Due to work scope limits, this study focused on only one of them. Otherwise, the working range is vast. Revit is the most widely used platform for building information modeling. This study only dealt with Revit software to restrict the work scope. Third, some terms have several meanings. Different words may be used depending on the person, country, and system. Because of the broad scope of work in this study, terms with several meanings were excluded from the scope of this study. Regardless of many limitations, this basic formal ontology modeling is a good starting point for future ontology-based research in the BIM domain. However, many shortcomings have to be addressed in future projects. In a future study, the author plans the following: (1) Develop a more basic formal ontology model in the construction area to share ontology as a knowledge base. (2) Convert various data forms of numerous platforms to a standard format to describe specific design conditions. (3) In terms of AEC, it includes terms with various meanings for more enhanced ontology. Finally, it is important to share the ontology model already created in each domain. In most studies, a domain ontology model has been created, but since it is not shared, it does not help when related studies are conducted. This ignores the most significant advantage of ontology. Another modeling starts despite the relevant domain. This creates confusion about the standard ontology workflow. So, to advance construction knowledge sharing and facilitate communication and collaboration, future study needs to create a sharing platform such as Onbee or Onfox in the construction field.

6. Conclusions

Numerous studies have been conducted to solve interoperability in the AEC domain. Various ontology applications and conceptual frameworks have been proposed. However, most developed frameworks or applications have not been fully applied or validated. Since most research has focused on building ontology-based applications or frameworks without building a BFO, proper validation cannot be performed without developing a BFO or domain ontology. In addition, if domain experts do the actual ontology modeling along with the developed conceptual frame, the domain experts may encounter unexpected difficulties, and it will take a lot of time and effort to solve this. Therefore, in order to build a better knowledge-sharing system, it is most important to establish a BFO knowledge base in the AEC field. In this study, the basic format ontology was developed in the BIM domain. This is also the first study to attempt to model ontology by reusing an existing BFO. Therefore, when conducting an ontology-related study in a BIM domain, domain experts can use the proposed basic formal domain ontology to save effort and time and obtain information about reuse. This is especially useful when extracting classes from domains and establishing the relationships between classes. It can also help to develop a complete domain ontology model, as it can be modified and supplemented for each project if it is partially available as needed. The BFO model proposed in this study can be reused as the basis for future BIM-related ontology research and future construction automation research and development. Future research should continue to study more precise relationships between term extraction and terminology. In addition, research should be continued to extract knowledge from other guides. Reusing existing domain ontology is strongly recommended to reduce the time and effort of developing an ontology for domain experts.

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