EXTENDING BUILDING INFORMATION MODELING (BIM) INTEROPERABILITY TO GEO-SPATIAL DOMAIN USING SEMANTIC WEB TECHNOLOGY

A Thesis
Presented to
The Academic Faculty

by

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In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy in the
School of Building Construction/College of Architecture

Georgia Institute of Technology
December 2014

EXTENDING BUILDING INFORMATION MODELING (BIM) INTEROPERABILITY TO GEO-SPATIAL DOMAIN USING SEMANTIC WEB TECHNOLOGY

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LIST OF SYMBOLS AND ABBREVIATIONS

AEC	Architecture/Engineering/Construction
API	Application Programming Interface
ATO	Assembled-To-Order
BIM	Building Information Modeling
BIMQL	Building Information Model Query Language
CAD	Computer-Aided Design
CEGIS	Center of Excellence for Geospatial Information Science
CSCM	Construction Supply Chain Management
DEM	Digital elevation model
DTM	Digital Terrain Model
ETO	Engineered-To-Order
FM	Facility Management
GIS	Geographic Information Systems
GML	Geographic Markup Language
GMO	Graph Matching for Ontologies
GPS	Global Positioning System
GVW	Gross Vehicle Weight
IFC	Industry Foundation Classes
IT	Information Technology
KPI	Key Performance Indicator
LEED	Leadership in Energy and Environmental Design
LiDAR	Light Detection And Ranging

MPG	Miles Per Gallon
MTO	Made-To-Order
MTS	Made-To-Stock
NBIMS	National Building Information Model Standard
NIST	National Institute of Standards and Technology
OGC	Open Geospatial Consortium
OWL	Web Ontology Language
RDF	Resource Description Framework
RFID	Radio Frequency Identification
TIN	Triangulated Irregular Network
URI	Unique Resource Identifier
USGS	United States Geological Survey
W3C	World Wide Web Consortium
WGS	World Geodetic System
XML	Extensible Markup Language

SUMMARY

Building Information Modeling (BIM) has been implemented for parametric modeling of buildings and associated infrastructure. It can support a wide range of design and construction applications such as quantity take-off, 4D simulation, and clash detection. However, as BIM applications become more sophisticated and used within other knowledge domains, the limitations of existing data exchange and sharing methods become apparent. Many of the pre-construction activities (e.g. site layout planning) do not fully take advantage of the benefits BIM provides to the design and construction practice, primarily because of the diversity of spatial relationships between topographic and temporary objects in a BIM environment. Once a BIM model is complete, building data can be incorporated in the form of an input into Geographic Information System (GIS) or other information system tools to streamline as many steps in the procurement and pre-construction processes as possible. While this indicates the presence of a gap in analyzing and processing temporary and spatial data within a BIM system, it also indicates the potential value of an integrated BIM model that can be used to enhance the current practice of integration and sharing of spatial information.

The integration of BIM and GIS can offer substantial benefits to manage the planning process during the design and pre-construction stages. BIM provides geometry, spatial relationships, and quantities of building components, GIS can use them to support the wide range of spatial analysis used in an early phase of the procurement process, and BIM can visualize the results of the GIS analyses in a 3D virtual world. Despite the practical applications of GIS technology to construction planning, it is not an easy task to

CHAPTER I

INTRODUCTION

Since the early 2000s, Building Information Modeling (BIM) has been used throughout the entire project lifecycle to facilitate effective project collaboration and integration of data and to support project activities. BIM involves smart 3D objects that include embedded data such as energy use data, lifecycle cost information, and quantities and properties of building components. It also supports a wide range of visualizations ranging from simple 2D plans to 3D photorealistic images of the building components. A building model (or BIM model) covers geometry, spatial relationships, and attributes of the building components, as well as parametric rules that automatically modify associated geometries when changes are made to a given building component. BIM was initially used for the planning and design phases of a project and is now used in the construction phase for a wide range of applications such as 4D simulation, clash detection and quantity take-off. Despite the successful applications of BIM in the design and construction stages, the use of BIM for pre-construction planning has not gained wide acceptance as in other phases of the project.

Many of the pre-construction activities (e.g. site layout planning) do not fully take advantage of the benefits BIM provides to the design and construction practice, primarily because of the diversity of spatial relationships between topographic and temporary objects in a BIM environment. Most BIM tools are designed to handle large number of permanent building objects and temporary structures have received far less attention. Modeling of temporary components within a BIM tool can offer substantial benefits in site layout and 4D planning. Also, the lack of spatial analysis capabilities in BIM underlines the need for utilizing spatial data analysis tools. For instance, the location of temporary structures is closely related to the spatial characteristics of the building elements and the obstacles existing in construction sites. There are factors, such as closeness (or proximity) relationships among the temporary structures and the building elements, which influence the desired location of temporary structures, but cannot be modeled with BIM.

There are many information systems that can be used to analyze, monitor, and manage the large amount of data (both spatial and non-spatial) involved in the concepts of procurement and pre-construction management. However, they rely on BIM models for the intelligent information about the project scope, materials and volumetric (geometric) properties. Engineers in the design and construction community utilize BIM to develop building systems and manage design geometry and site criteria, and once the building model is complete, building data can be incorporated in the form of an input into the information system tools to streamline as many steps in the procurement and pre-construction processes as possible. While this indicates the presence of a gap in analyzing and processing temporary and spatial data within a BIM system, it also indicates the potential value of an integrated BIM model that can be used to enhance the current practice of integration and sharing of spatial information.

This spatial data can be analyzed in large amounts by Geographic Information Systems (GIS). The GIS has been used successfully to solve the complexities of site layout planning and to support the wide range of spatial analysis used in the logistics perspective of the pre-construction activities. Having considered many different definitions, GIS is defined herein as a system of hardware, software, people, organization and institutional arrangement for collecting, storing, analyzing, and disseminating information about areas of the earth (Cromley and McLafferty 2012). Despite the practical applications of GIS technology to construction planning, it is not an easy task to transfer data from BIM to GIS or vice versa without consideration of data format and meaning.

Ways of combining data from different sources need to be found because there are a variety of database structures which can be used to store data about spatial (e.g. topography, facility location) and non-spatial (e.g. building material's carbon footprint) features. These include hierarchical data structures, network systems, and relational database structures (Crowther and Hartnett 2001). Data in hierarchical data structures have one-to-many or parent-child relationship, in which each relationship needs to be explicitly defined before the structure and its decision rules are developed. The objects or entities (e.g. building elements) in a BIM model are arranged in a hierarchy structure. Network systems are more suited for GIS applications because they are less rigid and can handle many-to-many relationships. This structure allows users to move from data item to data item through a series of pointers. Data are stored as ordered records or rows of attribute values (called tuples) in relational database. In general, GIS tools use relational database to collect, store, analyze, and present spatial and non-spatial data.

The integration of BIM and GIS can offer substantial benefits to manage the planning process during the design and pre-construction phases. While BIM systems focus on developing objects with the maximum level of detail in geometry, GIS are applied to analyze the objects, which already exist around us, in most abstract way. BIM provides geometry, spatial relationships, and quantities of building components, GIS can use them to support the wide range of spatial analysis used in an early phase of the procurement process, and BIM can visualize the results of the GIS analyses in a 3D virtual world. The major difficulty in combining BIM and GIS data is the incompatibility between these two technologies, the most obvious example being the modeling and reference system because the GIS data is always geo-referenced and in two or two-and-a-half dimensions while the BIM objects have their own local coordinate systems and the third dimension is of common use. Several studies have been conducted to explore the application of GIS technology in BIM environments and BIM models in the geospatial domain. However, these research efforts have focused on either BIM or GIS.

To develop a BIM-GIS model, it is essential to bring the benefits of both technologies together into a single comprehensive model. However, this integration suffers from a lack of interoperability across the GIS and BIM domains. For instance, construction site topography is typically modeled within a GIS as a raster map that contains regular grid cells and elevation values assigned to each cell. However, BIM authoring tools do not support raster-based terrain models. Even if the topographic data are transferred by other data formats (e.g. CSV file with x, y, and z-coordinate of each recorded terrain point), their precise meaning is not understood by the BIM platform. Different classes (e.g. bare ground, vegetation, body of water, and noise) in a GIS model are considered identical (e.g. topography surface) in a building information model. Moreover, since BIM authoring tools do not support the geospatial analysis needed in the process of locating temporary facilities, GIS can be leveraged throughout the pre-construction phase of a project. Although GIS tools can be used to manage spatial data analysis (e.g. model the construction site terrain and locate the temporary objects), a higher level of integration is needed to share information with and between BIM and GIS datasets. Again, even if the building data are exchanged by an interoperable format like Industry Foundation Classes (IFC), their precise meaning is not understood by the GIS platform.

The development and standardization of integrated data models have evolved from the electronic data interchange systems using a common data format to the current sophisticated internet services. Obviously, the transferring of the BIM and GIS data in their native formats, which is the lowest level of integration, is not efficient at all. It would clearly be preferable if users could effectively access data and methods from a different software program and exchange project information between heterogeneous platforms. The ultimate goal of research at this level of integration (i.e. syntactic interoperability) is to develop common data formats or descriptions that would facilitate the exchange of data across different platforms and applications. Because of the diversity and complexity of domain knowledge across BIM and GIS systems, however, syntactic approaches are not capable of overcoming semantic heterogeneity between building and geospatial information.

In order to fully integrate the GIS and BIM, there is a need for semantic interoperability solutions between these two platforms. Enabling interoperability at the semantic level is a key issue for bringing the benefits of both technologies together into one integrated solution. There are different approaches for the exchange and sharing of BIM and GIS information across the diverse resources, such as metadata for topological models, but it is not possible to search and retrieve temporal and geospatial data based on their content. For example, we can search and access spatial and attribute data stored within electronic drawings by keywords, but their content cannot be retrieved in this process. To model and visualize geospatial data in a BIM environment, the semantics of the GIS dataset need to be shared and delivered. This is done by annotating semantics of the GIS information to the shared reference ontology (Yang and Zhang 2006). This shared ontology is a set of building and geo-spatial terms - such as window, wall, terrain, lake and relations - that are specified with some indication of their meanings. Also, ontology identifies the relationships among these terms and distinguishes which terms have instances properties. In this study, building and geospatial information are given semantics (or well-defined meanings) by means of geospatial and Architecture/Engineering/Construction (AEC) domain ontologies, thus we can search and retrieve data by their content rather than just by keywords in metadata.

Semantic web technology is used in this study to convey meaning, which is interpretable by both construction project participants as well as BIM and GIS applications processing the transferred data. This technology was first proposed by the director of the World Wide Web Consortium (W3C) in the late 1990s, and it has since been applied to develop systems for knowledge structuring and integrate data across different applications. To accomplish this objective, each concept (or thing) should be labeled with a unique external reference, a Unique Resource Identifier (URI), and then useful information about the concept (e.g. description, content) can be provided by using semantic web standards. Once the relationships between the concepts are established, data can be shared across application boundaries.

The purpose of this study is to extend the interoperability of BIM authoring tools in geo-spatial domain by employing semantic web technology. To achieve this, we first translate building's elements and GIS data into a semantic web data format. Then we use a set of standardized ontologies for construction operations to integrate the heterogeneous spatial and temporal data in semantic web formats. Finally, we use a query language to access and acquire the data. The research questions that will be addressed in this study are presented in the following chapter. A description of interoperability between BIM and GIS is also provided in chapter two. How semantic web services can be used to provide semantic interoperability between BIM and GIS operations is addressed by the literature review. Then, the proposed methodology is described in chapter four. The feasibility and validity of the proposed methodology is discussed based on two use case examples and a case study. Finally, the feasibility of semantic web techniques and potential applications for construction industry are discussed in chapter six.

CHAPTER II

MOTIVATION and RESEARCH QUESTIONS

Considering the role of geometric properties and spatial relations among building components, integration of BIM and GIS is expected to improve the quality and effectiveness of decision-making during the design and construction phases of a project. While BIM systems focus on developing objects with the maximum level of detail in geometry, GIS are applied to analyze the objects, which already exist around us, in most abstract way. Therefore, to visualize existing topography and a new facility to be developed together we need more research on integrating the data models of BIM and GIS (Bansal 2011). Although these two technologies have evolved from distinctly different beginnings, both can benefit from each other if they could exchange data effectively. As BIM technology is mainly centered on indoor environment, GIS can extend the benefits and applicability of existing building models to the outdoor environment. By integrating building and geospatial information via standard-based methods, we can visualize, analyze, and model our facilities in their physical locations. The main benefits that a construction manager can expect from integrating BIM and GIS are described in the next chapter.

Several studies have been conducted to explore the application of GIS technology in BIM environments and BIM models in the geospatial domain. For instance, Isikdag et al. (2008) investigated the application of BIM in a geospatial context in order to improve the transfer and representation of information between these two domains. Choi et al. (2008) also established a prototype system to demonstrate the feasibility of BIM models to support indoor GIS applications. Peña-Mora et al. (2010), on the other hand, recognized the need to integrate different IT technologies, such as GIS, RFID and digital building information, in one reliable platform for emergency response management.

However, aforementioned research efforts have focused on either BIM or GIS. Real integration of BIM and GIS is achieved by using the strengths from both the BIM and GIS world in the context of the other, which has been recently proposed (Elbeltagi and Dawood 2011; Zhang et al. 2009). Before integration approach is developed, the advantages and differences between BIM and GIS should be considered. To develop a BIM-GIS model, it is essential to bring the benefits of both technologies together into a single comprehensive model. GIS builds upon existing information and objects; so, BIM should be used to create the building information. On the other hand, the lack of spatial analysis capabilities in BIM underlines the need for utilizing GIS. The major incompatibilities that exist between the technologies are listed in Table 1. Integrating these two technologies depends on the assumption that there are applications from both domains, which can maximize the value of both (Laat and Berlo 2011).

Table 1: Incompatibilities between BIM and GIS

	GIS	BIM
Modeling Environment	Mainly focus on outdoor environment. An outdoor activity may need to be positioned in GIS.	Focused mainly on indoor environment. Outdoors applications are limited to the outside of buildings. 3D modeling of site utilities and terrain modeling are also available in BIM.
Reference System	Geospatial data is always georeferenced. Objects are defined in a physical world with global coordinate systems or map projections.	BIM objects have their own local coordinate systems and a reference to a global coordinate system, for example at the left corner of the building.
Details of Drafting	GIS builds upon existing information and objects. It covers a large area with less detail and in smaller scales.	Drafting capabilities of BIM are utilized to develop larger scales with higher level of details.
Application Area	GIS is focused on urban and city areas.	BIM is rooted in the building and its attributes.
3D Modeling	GIS capabilities are limited to simple 2D shapes. Experimentation with 3D in GIS is in an early stage.	BIM is unique in its ability to work in full 3D environment. BIM has a rich set of spatial features and attributes.

In construction industry where a diversity of technologies and data sources applied throughout a project lifecycle, it is not surprising that there is a wide range of methods and tools currently in use for obtaining data from a variety of sources. A typical construction project requires integration and information sharing among different project participants and stakeholders across the various phases of the project life cycle. This can be seen in using different computer programs (e.g. BIM tools, 4D simulation applications, etc.) for modeling of construction information, where they rely on a wide range of distributed data sources. Processing and organizing geospatial and building data and creating solutions based on the combination of data and knowledge create a challenging and complex task due in large part to: (1) the vast amount of data generated; and, (2) lack of interoperability among the tools. Consequently, interoperability problems drive up integration costs across industry.

Because of the various domains involved in the building and construction industry, the development and standardization of integrated data models has gone through an evolution over the last 20 years, from electronic data interchange systems using a common data format to the current sophisticated internet services. At the lowest level of integration, users are now able to connect to a host and publish and download project information on the web, enabling project participants to transfer data files in their native formats without the need for specialist intervention. Such web services, which can be viewed as data or application interfaces, provide opportunities for exposing real-time and up-to-date building information (Underwood and Isikdag 2011). In the next level, which is called syntactic interoperability, users are able to directly access data and methods from a different software program and exchange project information between heterogeneous platforms (Underwood and Watson 2003). Syntactic heterogeneity describes the difference in representation format of data among different data sources. In the various models developed at this level, the emphasis is on integrating two or more data models into a single, unified, model (Karimi and Akinci 2009; Laat and Berlo 2011).

Most of these previous studies have primarily focused on BIM and GIS data conversion and transformation. For example, Wu and Hsieh (2007) proposed an approach to transform the geometric information of an IFC model into geometric objects for the GML model. Döllner and Hagedorn (2007) utilized the data integration capabilities of IFC to CityGML transformation in order to integrate data from CAD, GIS, and BIM applications into a virtual 3D city model. Nagel et al. (2009) provided conceptual requirements for the automatic transformation of IFC geometry to the different levels of detail in CityGML. Laat and Berlo (2011) developed an extension to map IFC classes and their properties to CityGML models and attributes. Hijazi et al. (2011) presented an approach for mapping information from IFC to CityGML in order to model interior utilities within a GIS context. Although these approaches have provided a range of means to enable data translation between BIM and GIS platforms, their applications are limited to solve interoperability problems at the syntactic level. Since these efforts cannot guarantee that the resulting model reflects the intended meaning of the data, the user needs to have knowledge about both systems and their functionalities. Due to the inconsistent level of details between IFC and CityGML data (e.g. non-existence of equivalent CityGML model for an IFC class), the syntax of two different BIM and GIS languages may never be fully translated. Semantic interoperability, which is the ability to structure and organize domain knowledge about an object or a phenomenon, provides integration at the highest level. This level of interoperability is further discussed in chapter four.

Given the overwhelming quantity of data available from multiple sources, the BIM is only one silo of information that can be seen as central repository of building data. The use of other relevant information, which may also exist in silos, in one particular building model becomes increasingly difficult with a lack of interoperability (Curry et al. 2013). Instead, it is worthwhile to expose geospatial and building data in a format that can be shared throughout the building's lifecycle and among various professional domains. By exposing such data in one of the fundamental standards of the semantic web, we can create links between them and provide a cloud of interconnected data (Curry et al. 2013).

The decision making process in a construction project is based on available information (usually extracted from different sources) coupled with the domain knowledge possessed by an individual. Each representation of an object or input in the individual's mind is tagged with a meaning. When making a decision, it is often not enough to merely access information; rather, it is necessary to understand the meaning of the acquired information. Figure 1 illustrates the current problem with a simple example, in which the construction site topography modelled by GIS is brought into the BIM tool. The screenshot on the left shows the digital model as a raster model in a GIS environment, while that on the right shows the (same) model in a BIM environment. Obviously, the transferring of the scanned data in their native formats, which is the lowest level of integration, is not efficient at all. The data are transferred by CSV data format including x, y, and z-coordinate of each captured point, however, their precise meaning is not understood by the BIM platform. At this level of integration (i.e. syntactic interoperability) different classes (e.g. bare ground, vegetation, man-made structure, and body of water) in the GIS model are considered identical in a building information model

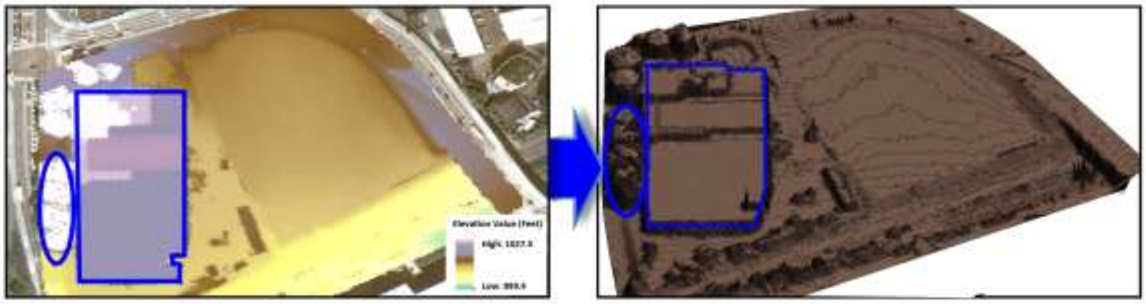


Figure 1: Data transfer from GIS (left) to BIM (right) with possible loss of semantics (identical models for different objects)

(terrain model in this example). A higher level of integration (i.e. semantic interoperability) is needed to share information and their meanings with BIM dataset.

Aside from being a highly collaborative, data-rich environment, BIM technology can help enable a more integrated, efficient project delivery by providing interoperability among heterogeneous and distributed data sources. Several studies have estimated the cost or lost efficiency due to lack of semantic interoperability. For example, Walker et al. (2005) estimated that US$77.8 billion per year could be saved by implementing an effective interoperability standard in health care information exchange and interoperability area. One study of the U.S. automotive supply chain estimated costs of over US$10 billion per year due to lack of semantic interoperability in that industry (Brunnermeier and Martin 2002). Also, a study prepared for the National Institute of Standards and Technology (NIST) by RTI International and the Logistic Management Institute estimated the cost of inadequate interoperability in the U.S. capital facilities industry to be $15.8 billion per year (GCR 2004) due to inadequate interoperability amongst computer-aided design, engineering, and software systems. Fu et al. (2007) demonstrated the importance of interoperability in life cycle costing, especially when dealing with building components in a BIM environment. McGraw Hill released a report in 2009 that stated a lack of interoperability between software applications at the top of the list of areas that need to be addressed to fully realize the benefits of BIM (Young et al. 2009).

Current state-of-the-art BIM (or GIS) tools enable the data exchange between the systems by using a common data format. Therefore, the users are able to access data from a different software program and exchange data within the BIM (or GIS) domain. However, it requires the user to have knowledge about both systems and their functionalities. Moreover, it is very time consuming and error prone for the user to figure out the meaning of data in the new system. The integration tools and current standards lack the ability to help the user to convey meaning, which is interpretable by both construction project participants as well as BIM and GIS tools. In order to fully integrate GIS and BIM, future work should focus on providing more interoperability at the semantic level.

The main contribution of this research is the development of a data framework, which not only connects data, users and tools, but also exchanges information in a meaningful way and with a minimum of human intervention. In order to achieve this objective, this study investigates the following key research questions:

(1) Why different BIM and GIS authoring tools cannot exchange and share their data models between each other?

(2) How BIM and GIS information can be exchanged and shared across the diverse resources?

(3) How heterogeneous spatial and temporal data can be semantically searched and retrieved by the BIM and GIS users?

Not only we cannot directly exchange a model from a BIM tool to a geospatial environment or vice versa, but also it is not possible to exchange a model from a given BIM tool (e.g. Autodesk Revit) with another one (e.g. Bentley Architecture). The reason for this lack of syntactic interoperability is due to the fact that two systems do not follow the same technical specifications for processing their base objects and their behaviors. The answer to the first specific research question leads to an assessment of specific data formats, communication protocols, and standards that provide syntactic interoperability. Syntactical interoperability is required for any attempts of further interoperability.

In order to answer the second question, both BIM and GIS information should be semantically described and categorized in a standard way. The answer to this question can make a valuable contribution towards managing the information exchange process and establishing a semantic interoperability among BIM and GIS systems. In order to answer the third question, we need to attach meaning to conventional concepts, which makes it possible to describe the domain knowledge. Ontologies provide a framework for representing, sharing, and managing domain knowledge through machine understandable descriptions that define the objects (taxonomies) and their associative relations across a domain (relationships) (El-Diraby et al. 2005). Enabling technologies such as the semantic web has provided standard taxonomies and ontologies for geospatial and construction knowledge.

This research shows how spatial (e.g. topography, facility location) and non-spatial (e.g. building material's carbon footprint) building data from different sources can be integrated and further analyzed to gain better insights into the design, construction, and operation processes. It is believed that enabling interoperability at the semantic level is a key issue for bringing the benefits of different technologies together into one integrated solution. Therefore, this research is aimed at extending semantic interoperability to pre-construction operations using semantic web services. Sustainable infrastructure projects require intense interdisciplinary collaboration from multiple fields including architecture, energy, materials, and multiple businesses and suppliers, each have their own tools to describe the domain knowledge. The primary objective is to bridge the lack of interoperability between the building modeling and geospatial analysis tools, which will enhance the efficiency and effectiveness of automated data acquisition and information sharing among project stakeholders.

CHAPTER III

LITERATURE REVIEW

The framework proposed in this research is utilized to ensure the highest level of interoperability between existing BIM and GIS technologies. This is achieved by applying semantic web techniques, which act as the medium through which BIM and GIS data can be shared, understood and processed by both tools. Three steps are involved in building semantic web application; ontology construction, semantic integration through interoperable data formats and standards, and query of heterogeneous information sources. Thus, this chapter is divided into four sections. First, some of the benefits derived from the integration of BIM and GIS are provided. Then, the last three sections provide further details on the steps involved in building semantic web application.

BIM and GIS Integration

As mentioned previously, we can use BIM capabilities to accurately provide existing information about the inside of a building and GIS to support the wide range of spatial analysis used in the logistics perspective (warehousing and transportation) of project. Building information models provide a very rich data source for properties about all of the building elements (e.g. identification information, maintenance information, and lifecycle condition-based information) that are inevitable components of any construction project. Moreover, descriptive information (e.g. transportation network, asset locations, etc.) in GIS should be used to model temporary components, locate temporary facilities, reduce transportation and logistics costs, and many other applications. Some of the potential applications that a construction manager can expect from integrating BIM and GIS are described in the following sections.

Design phase: digital modeling of building and landscape-level components

We transform data into information by adding values (e.g. through the use of an IT system) in different stages of a construction project. BIM is one of the many tools we use during the early stages of a project (e.g. design phase) to produce and manage building data. Azhar et al. (2011) demonstrated the ways designers and planners may use BIM for various sustainability analyses in pursuit of Leadership in Energy and Environmental Design (LEED) certification. BIM-based sustainability software generates analysis results for different building components more effectively than traditional methods. 4D models to show energy consumption of buildings at different temporal and spatial scales can be developed by linking the building model to energy analysis tools. In this approach, the capability of building information models to store multi-disciplinary information is utilized to access parameters necessary for performance calculations (Schlueter and Thesseling 2009). The 3D model generated by the BIM tool allows easier and more accurate visualization of a design at any stage of the process with the expectation that it is dimensionally consistent in every view (Deutsch 2011).

At any stage of the design, BIM technology can extract an accurate bill of quantities and spaces that can be used for cost estimation. It allows users to evaluate the functionality, economics and performance of buildings concurrently with building design in a popular 3D modelling environment (Cheung et al. 2012). Most complex projects in the AEC industries involve multi-disciplinary collaboration and the exchange of large building data set. During the past decade, the widespread adoption of object-oriented Computer-Aided Design (CAD) tools has generated more interests in BIM, as it facilitates simultaneous work by multiple design disciplines (Singh et al. 2011).

GIS used for geospatial analysis has proliferated within the construction industry in recent years. Its use in the construction industry has brought about a new way of thinking when meeting various construction project requirements. In design stage, its applications can be divided into two main groups according to the manner of the data acquisition: data management and topography visualization (Bansal and Pal 2007). There are now various GIS tools available in the market to store and manage attribute data, as well as provide the necessary editing capabilities. GIS improves construction planning and design efficiency by integrating spatial and non-spatial information in a single environment (Bansal and Pal 2009). Planning and designing of networked infrastructure require incorporation of both temporal and spatial aspects. Application of GIS toolbox led to a significant reduction in CO2 emissions and investment costs for transport and storage (van den Broek et al. 2010).

To fully utilize the benefits of BIM, we also require surrounding landscape-level data. However, modeling of the site topography still remains highly labor intensive and relies extensively on the project site surveys. Karan et al. (2014) explored an alternative approach for generating a digital model of site topography, in which remotely sensed data are used with GIS analyses. A terrain can be digitally modeled either by a series of regular grid points (altitude matrices) or as a Triangulated Irregular Network (TIN). The former is a raster-based model consisting of a matrix of grids where each grid contains a value representing surface elevation. Airborne LiDAR (Light Detection And Ranging), satellite imagery, and models provided by the United States Geological Survey (USGS) are three different sources of remotely sensed data that have been used in this study.

The elevation values derived from these digital models are compared with the values that have been measured in the field (by laser scanner). The spatial analysis functions of GIS were used to create a cell-based raster model of the four datasets and map the elevation differences between remotely sensed datasets and the values from the field measured dataset. This work showed that it is possible to generate the digital models of construction site terrain in a cost effective manner and with the required accuracy. Figure 2 shows four snapshots of the Digital Terrain Model (DTM) results (both raster and TIN) generated for a construction site. The height values as well as the calculated volumes for each result were compared with the values measured in the field to determine the accuracy of the DTMs.

Pre-construction phase: construction site layout planning

Having a 3D model of the building along with its surroundings (i.e. data) would allow managers to efficiently design a site layout (i.e. adding value) and identify optimal locations for temporary facilities (i.e. information). Sebt et al. (2008) explored the potential application of GIS to layout of temporary facilities on construction sites. Using GIS to identify optimal locations for temporary structures (e.g. site offices and lay-down areas) (Sebt et al. 2008), to reduce material delivery time (e.g. concrete) (Eskrootchi et al. 2008), and to assess the safety condition of construction sites (Karan and Ardeshir 2008) are examples of these applications.

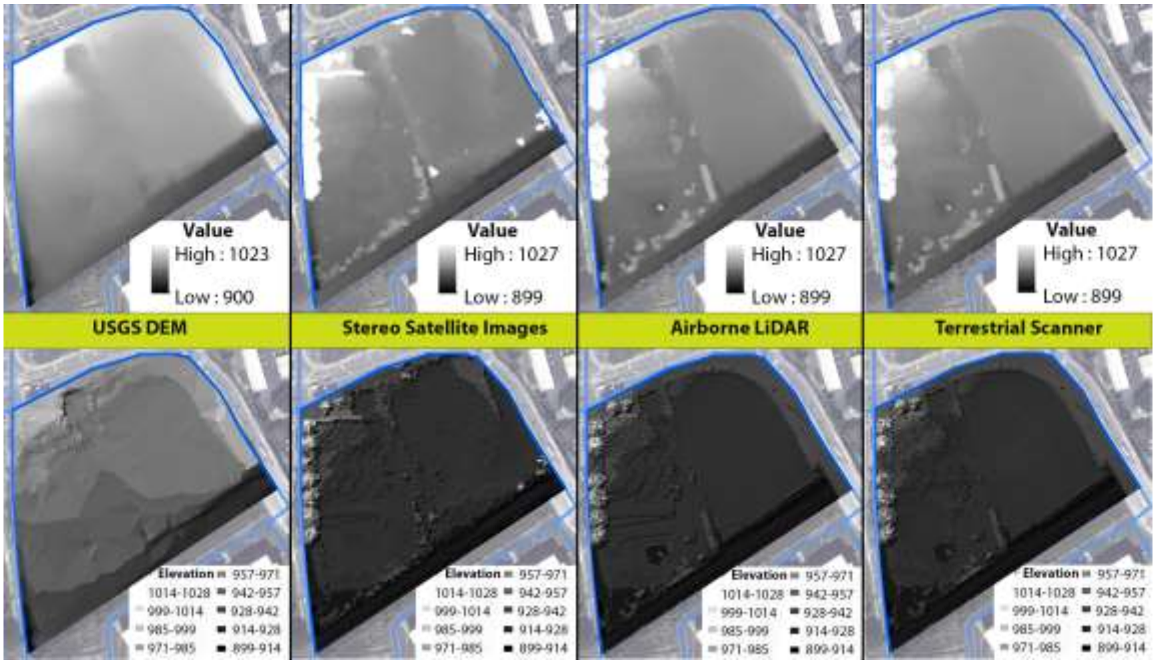


Figure 2: DTM representations of construction site terrain in raster (top) and TIN (bottom) formats (elevations are depicted in feet)

In order to define the properties of temporary structures, different parameters are defined to control the visibility of a temporary building in BIM and to detect the target objects in GIS. Determining the location of temporary facilities involves closeness (or proximity) relationships among the temporary and permanent facilities. The closeness relationships such as “close to”, “far from”, and “next to” represent the site layout objectives in minimizing the traveling time and improving safety. Far from (as opposed to close to) is usually applied for the facilities that have an impact on safety issues (e.g. electrical equipment and possible sources of sparks should be located far from flammable material). Formwork is placed next to the concrete element. Also, some relationships can be represented in a quantitative manner such as “within specified distance”. It is necessary to locate the supply points within operating radius of a tower crane. Figure 3 shows examples of the analysis results of the GIS and BIM for “scaffolding” (as a structural support) and “tower crane” (as equipment).

A concrete batch plants is one of the temporary facilities that has a significant impact on production costs (e.g. material delivery cost), especially in the case of large projects requiring high concrete volumes, or when transportation distances are too great for the supply of ready-mixed concrete. Therefore, the objective is to determine the

Figure 3: Locating temporary structures within GIS (left) and BIM (right)

location on minimum time-amount of concrete delivery through construction access roads. Delivery time is defined as the time elapsed from the concrete batch plant to the demand points. These points are permanent facilities requiring concrete. Using BIM, we are able to calculate the concrete required for the permanent facilities. Ideally concrete batch should be located as close as possible to their demand points to reduce travel time, however, this is often difficult to achieve in practice. The plan view of the permanent facilities, potential locations, and access roads for a construction project are shown in Figure 4. GIS technologies were used mainly to visualize, analyze, and combine data to retrieve spatial information, and the network analysis model (Figure 4) was completed within a GIS environment.

Hazardous material, crane's operating area, travel routes intersections, scaffolding, and falls and falling objects are examples of workplace hazards that could cause death or injury over a given time interval. The impact of these hazards on

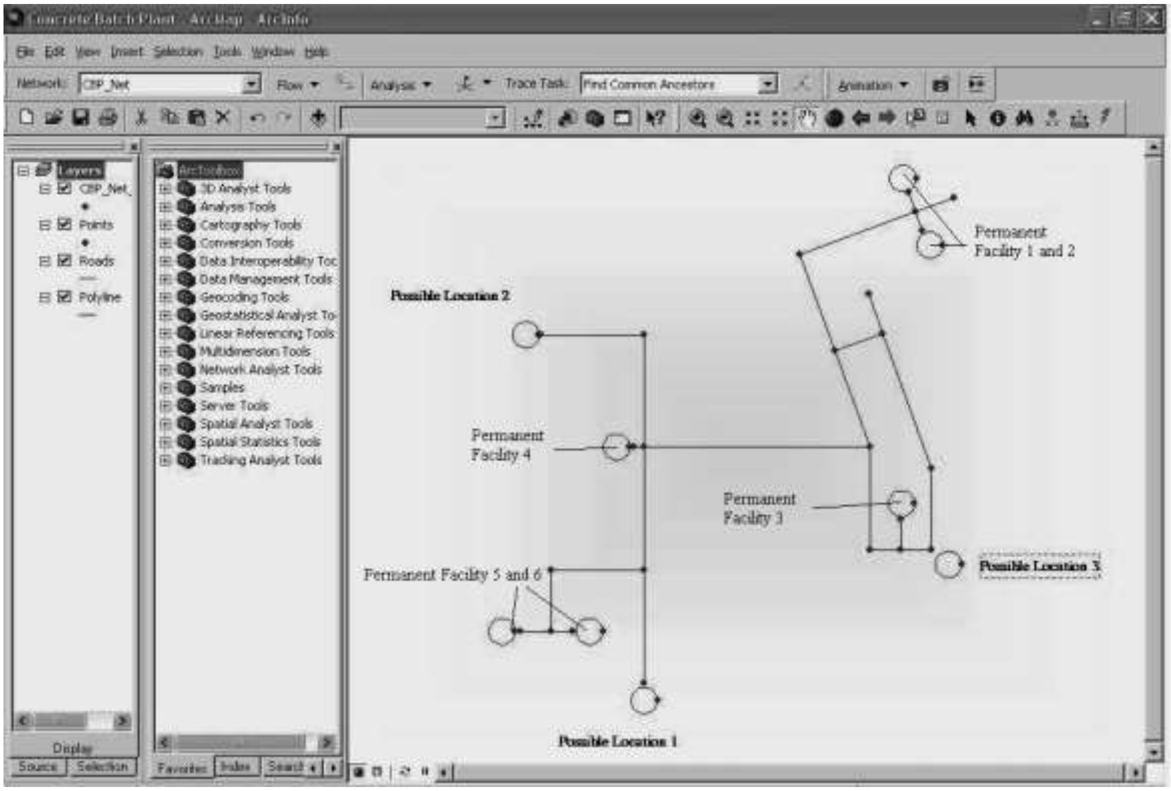


Figure 4: GIS application to reduce material delivery time

construction jobsite safety can be quantified by GIS. The task of computing safety indices for individual sites has an interactive relationship with building component information (e.g. space uses) and requires a great amount of spatial data. In response to these features, project managers can benefit from the availability of such information within the building model.

Identifying optimal number and location of tower cranes is one of the applications that brings the benefits of both BIM and GIS technologies together. The location and type of tower cranes are closely related to the shape, position and spatial characteristics of the loads and obstacles. This spatial data is mainly used in the process of location optimization for tower crane(s), which is possible to be analyzed in large amounts by GIS. The advantage of GIS-based methods is that they directly use spatial aspects of the construction site and display output in a suitable form to the user. For these reasons, GIS is found to be useful for such purposes. In addition, visualization techniques can be used to further enhance the functionality and integrity of GIS models. Zhong et al. (2004) and Bansal and Pal (2007; 2009) are among the studies that utilized the visualization capabilities of GIS.

However, due to the limitation of GIS tools in automated drafting and lack of semantic information about building elements, one can utilize different visualization tools. Regarding the distance between the crane's cab and load location, finding an optimal place for the tower crane plays an important role in improving operator's view. To respond to this need, it is appropriate to model the operator's viewpoint through the use of BIM. Furthermore, visual representation can be extended to monitor the crane's movements and to prevent the collision of tower cranes operating in a shared work zone. The snapshots generated by BIM are capable of appropriately representing the changing construction environment. Irizarry and Karan (2012) presented a new approach for integrating GIS and BIM that enables managers to visualize the 3D model of tower cranes in their optimal locations. In their research, GIS is used to develop a crane location model where closeness relationships are generated by means of spatial analysis function and BIM is employed to develop building models and to visualize the results of the GIS model in a 3D virtual world. In this sense, BIM provides the model with the capability to simulate the operator’s viewpoint in order to detect potential collisions between tower cranes and objects in the worksite environment. The locations derived by the proposed model, compared to the actual locations, resulted in a reduction of the conflict between tower cranes and their surroundings by about 16%. The plan (GIS environment) and 3D view (BIM environment) of a construction site are shown in Figure 5, in which tower cranes are located in their optimal locations.

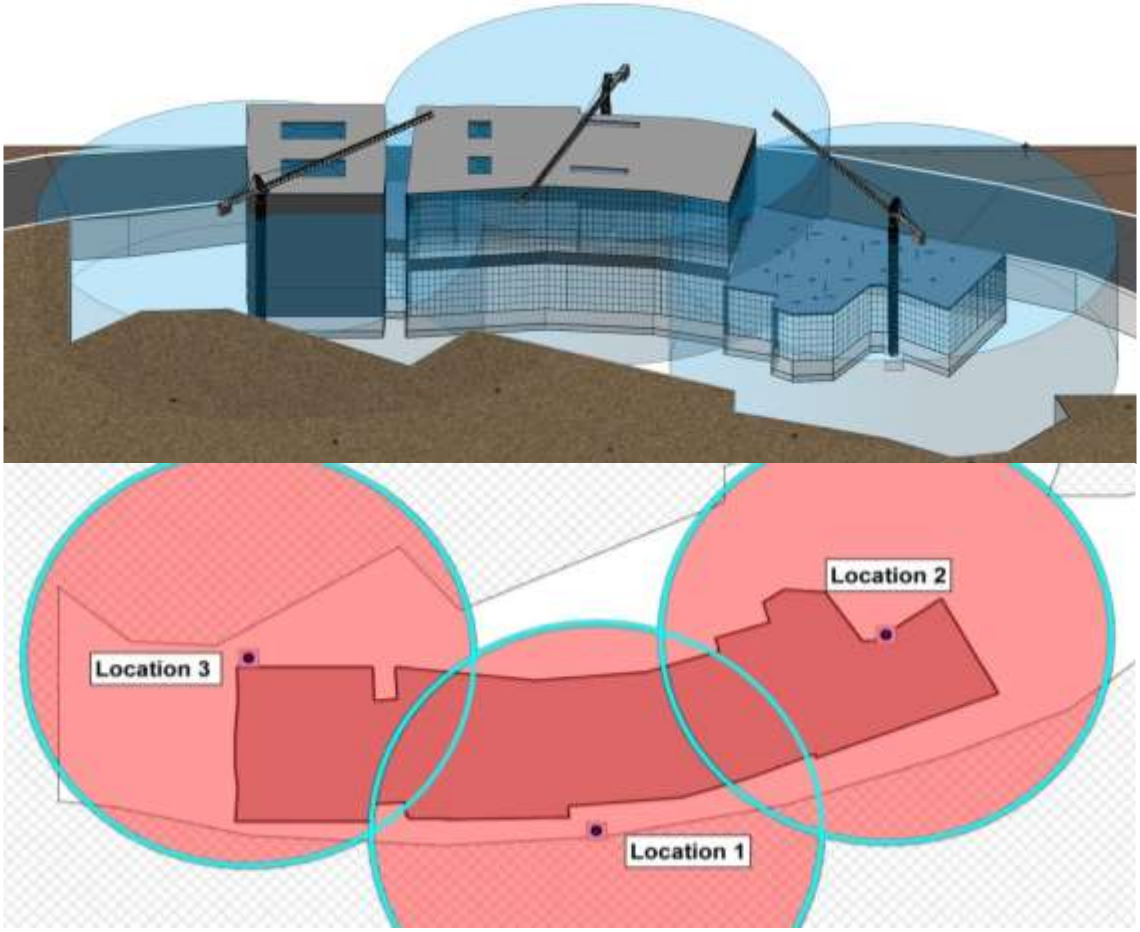


Figure 5: 3D BIM (top) and GIS plan (bottom) views for optimal locations of tower cranes

Construction phase: supply chain management:

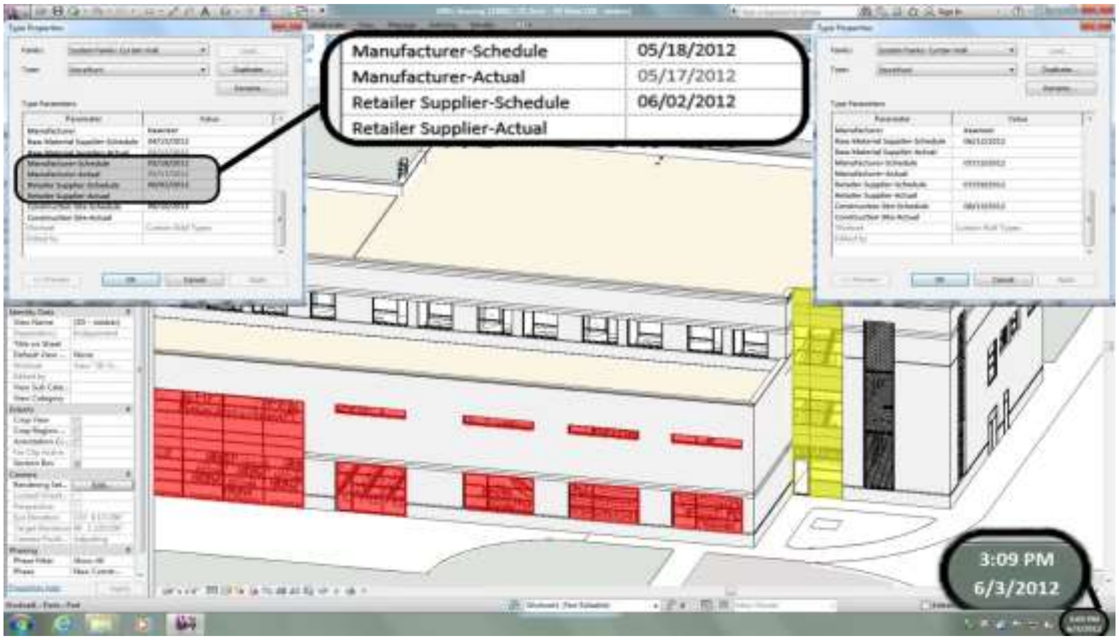
The construction stage is when the detailed supply chain operation and coordination take place. In this phase, one objective is to utilize supply chain management strategies to improve the performance of construction and reduce large waste caused by inefficient materials management. In order to support this objective, Irizarry et al. (2013) integrated BIM and GIS into a unique system, which enables keeping track of the supply chain status and provides warning signals to ensure the delivery of materials. Various information technology (IT) applications have been used in the literature as a way to improve the integration process of construction supply chain management (CSCM). The GIS is another IT system that has been proposed in the literature. Among them, Cheng and Yang (2001) developed GIS-based cost estimates in order to identify options and solutions for problems regarding materials layout. When GIS layout data is linked with three dimensional (3D) site models, the whole material circulation path in the site can be vividly simulated (Ma et al. 2005). The substantial input data required in the CSCM is often derived both from automated sources (software applications, bar code readers, sensors, and analytical instruments) and manual interactions (Cutting-Decelle et al. 2007). In this regard, an automated system that integrates radio frequency identification (RFID) and global positioning system (GPS) technologies with GIS for tracking resources can eliminate labor-intensive data collection and limitation of distance of line-of-sight (Ergen et al. 2007).

With the use of IT–based tools such as BIM, supply-network visibility and accurate information concerning the status of material at different stages can be enhanced (Young et al. 2011). As a result, the managers have access to a BIM model with the full range of material information (Goedert and Meadati 2008). Having a parametric model that includes precise BIM components makes it possible to define discrete quantifiable elements to show detailed material and component properties (Leite et al. 2011). These quantities, which are provided by BIM tools, can be exported to a spreadsheet or an external database, and must include the material to be procured, both temporary and permanent (Alder 2006). Some issues may arise when an element does not exist in the building model (e.g. scaffolding) or a needed quantity cannot be calculated based on the component properties. Quantities that cannot be extracted from the building information model directly would need to be manually entered. To evaluate logistics constraints involved in the material delivery process, GIS is used to map the entire supply chain process, e.g., location of suppliers, transportation, value adding, and nonvalue adding activities. In this sense, the GIS module of the system uses descriptive information (e.g. transportation network) and geographical location of suppliers in order to provide an ideal solution to manage costs of transportation (Li et al. 2003).

Figure 6 shows an example of how the status of material (e.g. curtain wall) is visualized in the BIM environment. The red color indicates that those “curtain walls” have a possibility of causing the delay, while the yellow color for the other elements means that no actual dates are provided for those “curtain walls”. Also, for the purpose of simplicity, the parameters entities are enlarged in the current view. As can be seen, the entity for “retailer supplier-actual” date is empty (null), and because the current date (i.e. 06/03/2012) value is greater than the “retailer supplier-schedule” date, the status color is returned as “red”. This capability provides managers with reliable information on material status.

Operation phase: facility management

As one of the last stages, facility management (FM) is about the planning and managing the life cycle of a building. Obviously, facility managers need a massive amount of information for their work. Karan and Irizarry (2014) developed a spatial data framework, which can offer facility managers an integrated tool to manage the maintenance and repair processes of FM. The concept of semantic web is applied in this study to provide semantic interoperability between FM operations. BIM tools provide information-rich models of the built-environment with the capability to incorporate a variety of as-built building and equipment information. The richness and reliability of the information provided by BIM enables facility managers to populate and edit the FM database in a faster and more accurate way. The database includes information about the maintenance operations, scheduled parts replacement, and work orders for every piece of equipment. Linking FM-related information with the building model can help better visualize the FM process and ensure rapid response to clients' needs (Eastman et al. 2011). Having the related installation and supplier's information, the facility manager is able to deal with service calls or customer service more efficiently and take any necessary action to ensure that the complete system is functioning appropriately. The required information can be accessed from a BIM model that contains essential information about any installed equipment, such as warranty, service contract, manufacturer data, and status on repair.



Manufacturer-Schedule	05/18/2012
Manufacturer-Actual	05/17/2012
Retailer Supplier-Schedule	06/02/2012
Retailer Supplier-Actual	

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Figure 6: Generation of a 3D color-coded view of "material (e.g. curtain wall)" in the BIM model

The rapidly evolving commercial software applications and tools that support BIM for FM is causing professional associations and standards organizations to offer data exchange mechanism for the adoption and use of building information models. Among these organizations is the National Building Information Model Standard (NBIMS), under the direction of the buildingSMART alliance, which developed IFC as a neutral standardized and industry supported data exchange mechanism for sharing building information models (Teicholz 2013). The IFC Model is developed as a set of modules, and each module provides further model detail within the scope requirements for individual domains such as architecture, structural engineering, FM, and so on. The FM domain is based on four layers of schemas defining basic concepts that support information exchange and sharing within the domain of interest of the facilities manager. These schemas are:

(1) IfcFacilitiesMgmtDomain,

(2) IfcSharedMgmtElements

(3) IfcSharedFacilitiesElements

(4) IfcProcessExtension.

As can be seen, the above schemas of IFC addresses many FM processes, objects and relationships (Mitchell and Hans Schevers 2007).

GISs are a computerized tool designed to map and analyze geographic relationships between spatial objects, and offer many benefits to the FM community by displaying building assets, such as utilities and landscape infrastructure, in a digital map format. GIS has been used successfully in various areas of FM, including space management, visualization and site planning, operation and maintenance services, and emergency management, as well as SCM applications. The use of GIS to fulfill the demands on space and inventory management for rooms and building on University of Texas at Dallas campus is a good example of these applications (Valcik and

Huesca- Dorantes 2003). The result was the spatial inventory database, which includes a georeferenced database linked to nonspatial data through the use of GIS. The system uses descriptive information (e.g. transportation network) and groups building and site work orders based on asset locations to reduce transportation and logistics costs.

In order to achieve logistics' aim of reducing costs, while simultaneously improving customer satisfaction, we can reduce costs due to reduction in inventory costs and lead times, and aggregate different demands into one pool of storage. To do this, GIS analysis requires information such as the locations of customers, inventories and manufacturing resources. While GIS systems mainly focus on outdoor environment, BIM technology is available to register objects inside of a building. FM workflows require work both inside and outside buildings and across the entire supply chain. Integrating BIM and GIS in a spatial data framework can provide an effective way to apply geospatial analysis and visualization to FM processes that occur inside and outside buildings. Liu and Issa (2012) utilized both technologies for detecting and mapping pipe network information. Although the study mainly relied on BIM and GIS visualization capabilities, it showed how facility managers can benefit from an implementation of BIM in geospatial context. Despite these benefits, there are only few FM software products that accept the input of BIM and GIS together. Figure 7 shows the FM commercial software products that have links either to BIM or GIS. The primary barrier lies with lack of interoperability across different data formats used in the FM supply chain.

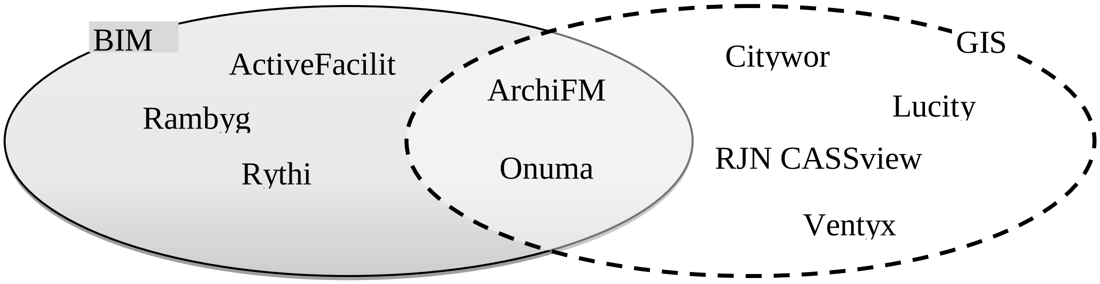


Figure 7: FM software systems with links to BIM or GIS

Ontology-Based Approaches for Improving the Interoperability

The current approach to exchange and share building data between BIM applications is based on the exchange of IFC files. While this approach was, and still remains, an effective way to hold and exchange data among various participants in a building, construction or FM project, it does not provide semantic-based representation of knowledge, and thus limits the capability of inferring additional knowledge (Törmä et al. 2012). Therefore, the use of BIM outside of AEC domain or few engineering domains that use IFC, and more specifically EXPRESS modeling language, is very limited. Description logics provide means for managing semantic contents and representing distributed knowledge in a given domain of application (Zhang et al. 2007). The way description logics are able to describe an application domain, in terms of its concepts (or classes) and their properties and relationships (or roles), forms a formal foundation for modern ontology languages. After a brief review of ontology-based approaches in the AEC domain of knowledge in this section, the next chapter describes how the IFC schema can be lifted onto an ontological level by using description logic.

Anumba et al. (2008) reviewed examples and case studies of ontology-based information and knowledge management systems in the construction delivery process and found that middleware applications, such as semantic web, have the potential to meet some of the technical challenges inherent in the development and use of ontologies for construction information. The e-COGNOS Project (Consistent knowledge management across projects and between enterprises in the construction domain) was one of the first attempts to develop a comprehensive ontology-based system in the construction domain (Lima et al. 2003). This project was funded by R&D organizations (University of Salford from UK, and CSTB from France) as well as four end users that are major actors of the construction industry in Europe (HOCHTIEF from Germany, OTH from France, YIT from Finland, and Taylor Woodrow from UK). Some of the previously developed classifications and taxonomies (e.g. the IFC model, the British Standard Glossary of Building and Civil Engineering terms, the Uniclass, and the W3C DAML+OIL language) were adopted and reused to support the consistent knowledge representation of construction items (Lima et al. 2005). Toward this objective, El-Diraby et al. (2005) presented a domain taxonomy that was developed as part of the e-COGNOS project. The taxonomy uses seven major domains to classify construction concepts: Process, Product, Project, Actor, Resource, Technical Topics, and Systems. Another study (Wang and Xue 2008) adopted the e-COGNOS and presented an ontology-based semantic blogging system to facilitate information categorization and retrieval. Based on this project, El-Gohary and El-Diraby (2010), and El-Diraby and Osman (2011) presented an ontology for the infrastructure and construction domain that relates to construction aspects of infrastructure products.

Despite the successful applications of e-COGNOS identified in their research, the next step is to develop a formal ontology for construction that allows a user to share and manage domain knowledge. If we define taxonomy as a set of terms and their definitions that are organized by a hierarchy, ontology provides a framework for representing a concept by its position in the hierarchy and its relationships to other concepts. The result of the e-COGNOS project was a pure taxonomy that only contains construction terms and their relations in a taxonomic tree. Further research is required to explore the full capability and benefits of mapping this construction-specific taxonomy with other ontologies.

There have been many applications of ontology-based approaches in civil and construction engineering. Yurchyshyna and Zarli (2009) presented an ontology-based method for the formalization and application of construction conformance requirements for effective code checking. Wang and Boukamp (2009) adopted ontological modeling to organize essential concepts of job hazard analysis knowledge and identify applicable safety rules. Elghamrawy et al. (2009) developed a framework that relies on the use of concept ontologies for describing and indexing the construction problem context information captured through the use of RFID. In a similar effort, Sørensen et al. (2010) created a digital link between the virtual models and the physical components in the construction by means of RFID technology and reviewed existing ontologies for information sharing between trading partners, easy access of information, and reading of data stored in electronic tags. Wang et al. (2010) proposed an ontology-based approach to facilitate the management of context-sensitive construction information that is stored in different textual documents. Zhong et al. (2012) proposed an ontology for construction quality inspection and evaluation, CQIEOntology, for improving the support to the construction quality inspection and management. Park et al. (2013) proposed a conceptual system framework for the proactive defect management with three inter-related system solutions; defect data collection template, defect domain ontology, and augmented reality. Another study used BIM data and ontology to automate the selection and matching work items to the elements of buildings and their materials (Lee et al. 2013).

When managing a construction supply chain, ontology can be used to integrate different heterogeneous systems. Pandit and Zhu (2007) proposed to use ontology to facilitate efficient and effective information sharing between the collaborating information systems and evaluate available design alternatives from heterogeneous data sources. Kim and Grobler (2007) utilized an ontology to provide an underlying structure of objects and relationships of a building for automatic reasoning about the conceptual design process. The ontology is documented in the language of description logics to represent the knowledge of an application domain. Fuertes et al. (2007) developed an ontology for the document management systems used in AEC/FM with the aim of reducing the interoperability and information exchange problems.

A number of studies have been conducted to estimate the effectiveness of ontology-based techniques in systematizing the process of risk management. Tserng et al.

(2009) developed an ontology-based risk management framework to decrease risk threats to the project. Fidan et al. (2011) demonstrated a formal ontology for relating risk and vulnerability to cost overrun. Jiang et al. (2013) provided an ontology-based semantic retrieval method to facilitate utilizing previous projects' experience for risk management of construction project.

Despite the contributions and practical features of the above ontology-based approaches, research on the potential application of ontology-driven on the integration and interpretation of heterogeneous information resources is very lacking. One of the few relevant researches is the attempt of El-Gohary and El-Diraby (2009) to develop an ontology merger (Onto-Integrator) based on semantic similarity comparison methods to merge concept taxonomies and ontological relations of source ontologies into an integrated combined ontology.

Interoperable Formats for Exchanging Data

IFC is the most well-known interoperable format for the uniform representation and exchange of project information throughout the construction community. The IFC is developed by buildingSMART® to facilitate the software interoperability for buildings and architecture (Yang 2003). It provides a range of means to define building objects (beam, column, wall, slab, etc.), with associated attributes and properties, and other information in a publicly available data schema (Eastman et al. 2009). In addition to normal attributes that are used to define an IFC element, there are optional attributes that give additional information about the element but their value is optional (not always needed and can be assigned a null value). The IFC was designed and written using the EXPRESS schema that includes building objects and relationships between them. These building objects are defined by a hierarchical entity structure, in which objects (or entities) are related by subtype/supertype relationships and/or by attributes. An attribute is declared by a name and a data type. The data type defines the format of the attribute value. The attribute values are used to further specify the semantics of the properties assigned to the IFC entities. These explicit attributes along with the constraints and structure of IFC document are defined on a schema level.

Although IFC is a versatile standard, it has been developed to support the frequent exchange of small amounts of data between interrelated participants within the building construction process. There might be the need for the exchange of large volumes of data over wide area networks, such as the Internet. The use of Extensible Markup Language (XML) and its related technologies can overcome the aforementioned problems (Bakis et al. 2007). The construction industry has recognized the importance of XML technology applications in sharing and exchanging structured data between different parties. AecXML to cover resource and activity-related data interchange, TransXML for the transportation data exchange, LandXML for survey and road design schemas, and DiggsML as a geotechnical construction data interchange standard are some of the standards developed by national/international consortiums to provide the industry with international data interchange standards (Agdas and Ellis 2010). In the XML schema, a variable or object and its attributes are classified by data types (e.g. Boolean, integer, etc) and constraints (that are expressed by axioms) are used for describing the structure and contents of XML documents.

The Open Geospatial Consortium (OGC) introduced the Geographic Markup Language (GML) for data interoperability in the geospatial community. GML allows complete data transfer between different databases and application software, which results in application schema (Peachavanish et al. 2006). In order to demonstrate and promote such standards, OGC initiated collaborative efforts (such as the interoperability program) in the 3D domain, which resulted in many opportunities and discovered issues related to CAD-GIS-BIM architecture (OGC 2007; OGC 2008). Another important effort is CityGML, an open data model and XML-based format for the storage and exchange of virtual 3D models. It is implemented as an application schema for the GML3 (OGC 2008). While recent attempts to integrate BIMs within CityGML models have value, there are some limitations to encompass a comprehensive BIM-GIS solution. For example, CityGML has been limited in use to exterior buildings and their surroundings. Although much of the IFC contents are specific to the building, buildingSMART has been working on extending the scope of IFCs to other civil engineering domains, such as GIS-based systems. In this context, the Industry Foundation Classes for Geographic Information Systems (IFG) has been developed for enabling the exchange of geographic information in GIS with the IFC schema (see http://www.ifcwiki.org/index.php /IFC_for_GIS). However, the prospect of achieving full-fledged semantic interoperability among users depends on the degree of agreements at both the application level and the tool level (Peachavanish et al. 2006).

Similar to the role of IFC in the construction industry to exchange and share data between BIM applications, the semantic web uses the Resource Description Framework (RDF) and Web Ontology Language (OWL) as standard data exchange formats to represent and share information in machine- and human-readable form. The RDF data model represents a relationship (or a predicate that donates a relationship) between a subject and an object. These three statements are often referred to as 'RDF triples'. As an example, "The light pole is made of steel" can be represented in RDF as this collection of triples; a subject donates "light pole", a predicate donating "is made of", and an object donating "steel". In addition, each concept (subject or object) and relation may be labeled with a short string, a URI, thereby making the RDF graph explicitly labelled. The usage of URIs in RDF enables the description of information in very diverse and disparate groups while preserving its original interrelations (Pauwels et al. 2011). Thus, the proposed methodology utilizes the capabilities of ontology languages to represent RDF query results as IFC building models.

Query-based approaches for information retrieval

A query language is needed to retrieve and manipulate data stored in semantic web data format and select the correct building data. SPARQL is the standardized query language for semantic web, which retrieves and manipulates the data stored in the standard data models. Although there are several formats to represent the SPARQL query results, there is no universally accepted standard that is compatible with existing BIM tools. The results of SPARQL queries can be displayed as HTML, CSV, Spreadsheet, JSON, and RDF graphs, none of them are compatible with existing BIM tools. Thus, this study focuses on the development of a process for query and access to ontology-based web services. This process converts the query results from SPARQL into ifcXML, which allows BIM users to query and retrieve building data at any time over the web from heterogeneous data providers.

Although query-based approaches have received considerable attention in terms of research and commentaries, very little research has been conducted in the construction industry for extracting and retrieving building related information for BIM applications. As can be seen from Figure 8, which shows the gap in the existing literature, the focus is mostly on the extraction and querying of information from a BIM. But how can we bring the query results into the BIM model? Examples of these efforts include the Partial Model Query Language (Adachi 2003) and the Product Model Query Language of the EuroStep Model Server, both provide query support for the retrieval of IFC properties and spatial relationships. Borrmann et al. (2006) provided formal definitions for 3D spatial data types as well as the directional, topological, metric and Boolean operators to outline the implementation of spatial query language for BIMs. Nepal et al. (2012) described the process and methods of extracting spatial data directly from a BIM model and representing it in a common XML format. Mazairac and Beetz (2013) introduced BIMQL (Building Information Model Query Language), an extendable, open, domain specific query language for building information models to allow the selection and partial modification of model instances. The research findings indicate that the format of query output is considered the most important component of building information query results.

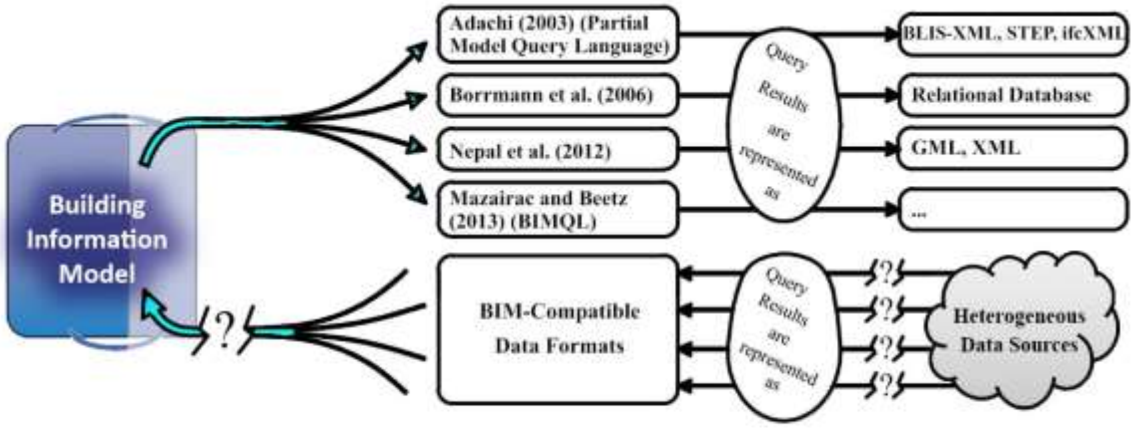


Figure 8: Query-based approaches and trends in the existing BIM literature

CHAPTER IV

RESEARCH METHODOLOGY

The methodology for extending BIM interoperability to geo-spatial domain consists of five stages. First, an IFC-compliant ontology describing the hierarchy structure of BIM objects, their relationships and their properties is developed. The emphasis is on semantic indexing and retrieval of building information from an IFC model. Second, ontology mapping is used to link similar relationships or concepts between the source (e.g. BIM) and target (e.g. GIS) ontologies. The output is an extended ontology that contains all classes and properties from both BIM and GIS domains, which are relevant to the case study and use cases examples. Then, building's elements and GIS data are translated into RDF/OWL format, thus can be processed by semantic web applications. Once the information has been gathered from different sources and transformed into an appropriate semantic web format, the SPARQL query language is used in the fourth section to retrieve this information from a dataset. Also, a new process is developed to translate semantic web query results into the XML representations of the IFC schema and data. Finally, the completeness of the methodology is validated through a case study and two use case examples.

Figure 9 demonstrates the process of establishing semantic interoperability and integration and the activities supported by each stage. Since the purpose of this study is to bridge the gap between BIM and GIS models at the semantic level by employing semantic web technology, the next sections first discuss different levels of interoperability and describe how semantic web technology can be used to connect the BIM and GIS data together in meaningful ways. Each step in the process is explained in detail in the following sections. This study adopts ontology mapping methods that are being increasingly used to map BIM and GIS ontologies in the second stage, Integration.

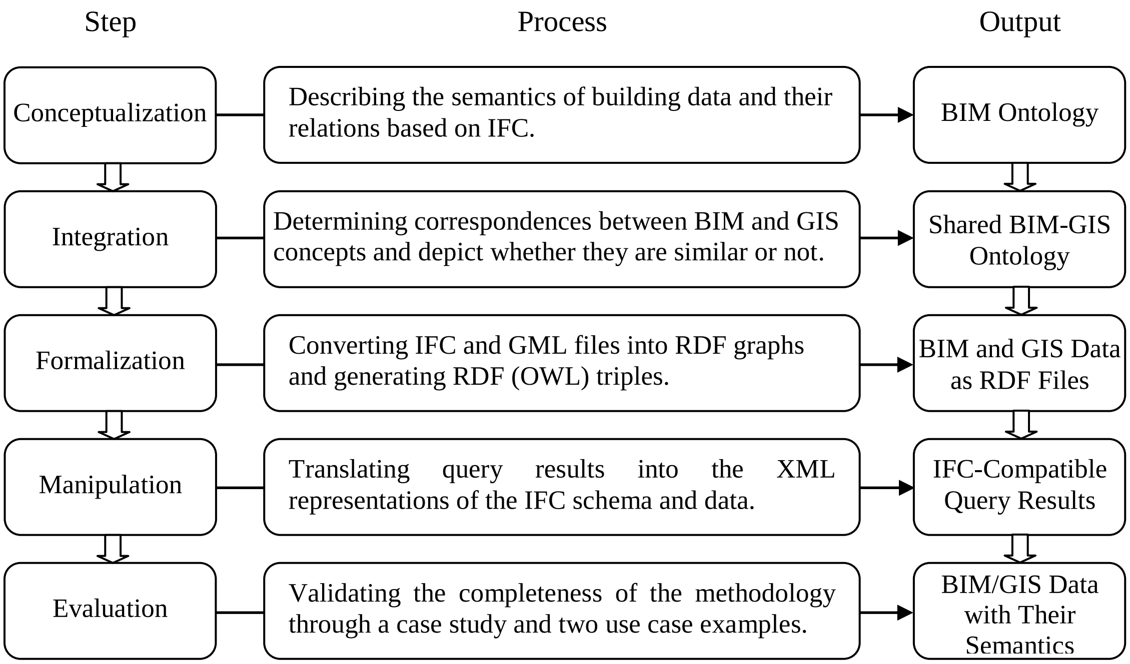


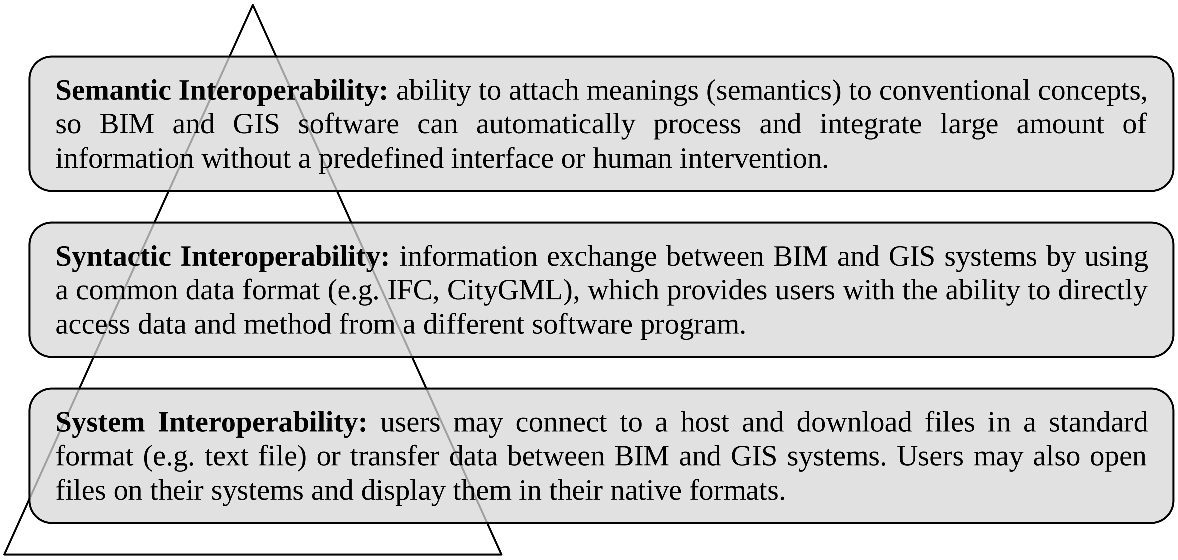
Figure 9: Research methodology process

Different Levels of Interoperability

The interoperability between BIM and GIS can be presented in different levels (Bishr 1998) (Figure 10). At the lowest level, users may connect to a host and download files in a standard format or transfer data files between BIM and GIS systems. Users may also open files on other systems and display them in their native formats. However, the main disadvantage is that users are not able to search and manipulate distributed databases (Goodchild et al. 1999). The next level (i.e. syntactic interoperability) is about the data exchange between BIM and GIS systems by using a common data format, which provides users with the ability to directly access data and methods from a different software program (Karimi and Akinci 2009). IFC is the most well-known interoperable format for exchanging data throughout the construction community.

Semantic interoperability provides interoperability at the highest level, which is the ability to attach meaning to conventional concepts. This is used to structure and organize domain knowledge about an object or a phenomenon in such a way that software can automatically process and integrate large amount of information without a predefined interface or human intervention (Kalfoglou 2009). The key to achieving interoperability at the semantic level is to make sure that the relationship between two different disciplines is maintained during data transfer (Peachavanish et al. 2006). In computer science, ontologies were adopted to define the standard taxonomies and services to facilitate sharing and reuse of domain knowledge (Davies et al. 2003).

In this study, we consider the semantic web as a common framework for providing semantic interoperability between BIM and GIS operations in order to transport meaning that is interpretable both by (1) construction project participants and (2) BIM/GIS applications processing the exchanged information. To achieve this, the information should be semantically described and categorized in a standard way. The next section discusses the concept and summarizes the various uses of the semantic web in construction domain.



Semantic Interoperability: ability to attach meanings (semantics) to conventional concepts, so BIM and GIS software can automatically process and integrate large amount of information without a predefined interface or human intervention.

Syntactic Interoperability: information exchange between BIM and GIS systems by using a common data format (e.g. IFC, CityGML), which provides users with the ability to directly access data and method from a different software program.

System Interoperability: users may connect to a host and download files in a standard format (e.g. text file) or transfer data between BIM and GIS systems. Users may also open files on their systems and display them in their native formats.

Figure 10: Different levels of interoperability between BIM and GIS systems

Interoperability through Semantic Web Technology

Generally, semantic technologies aim at exchanging information in a meaningful way and with a minimum of human intervention. Due to the nature and large amount of data needed to transfer between BIM and GIS systems, semantic web appears to be the best fit compared to other semantic technologies such as artificial intelligence, classification and data mining. The nature of the information in the geospatial and AEC domains is decentralized and multidisciplinary, which hinders the wide adoption of artificial intelligence models by BIM and GIS practitioners. The integration of BIM and GIS is more about data than logic and reasoning in a centralized data model like artificial intelligence or expert systems. Although classification technologies can help BIM or GIS users to quickly and efficiently retrieve small amounts of data, they are not likely to support the scale of data sharing between BIM and GIS applications. Data mining technologies can be used to analyze large amounts of data, however, the user needs to have knowledge about the data in order to supply the correct data and make conclusions out of the resulting data.

Semantic ambiguities of different GIS and building data sources are one of the major obstacles to effective data interoperability. For instance, “obstructions near lay-down areas” may raise ambiguous interpretations in the geospatial and the building domains. Obstructions are composed of many permanent objects as well as temporary structures located around the lay-down areas. Different metadata creators may use different names for the obstructions. Also, the scales of the two entities, “obstructions” and “lay-down areas”, are mismatched. Most of such ambiguities can be resolved by means of ontology and utilizing the knowledge of operators. As all geographic objects have their physical scales, different physical scales such as 0 square feet, 10 square feet, and 100 square feet can be used to interpret the semantically ambiguous words “obstructions” and “lay-down areas”.

The semantic web technology represents a fundamentally new way of formatting data that can be processed directly and indirectly by machines (Schraw 1998). According to the W3C, the standard enables the description of information together with its inherent semantics to be shared and reused across application and community boundaries (Vos et al. 2011). Semantic web technologies have been used by several researchers to facilitate construction project information sharing. Anumba et al. (2008) explored the use of semantic web technologies to meet the challenges of collaborative project information management. Beetz (2009) demonstrated the feasibility of the semantic web tool to address information exchange and integration problems in AEC interoperability. Akinci et al. (2010) developed a web-based approach to enable semantic interoperability between CAD and GIS platforms. Niknam and Karshenas (2013) presented a new approach to construction cost estimating using the semantic web technology. None of the previous models have demonstrated the potential application of semantic web as a common framework for providing semantic interoperability between BIM and GIS operations. Venugopal (2011) adopted an ontological framework, similar to that of Semantic Web, in order to provide a formal classification structure for IFC implementations for the domain of Precast/ Prestressed Concrete Industry.

To semantically search and integrate heterogeneous spatial and temporal data between BIM and GIS, a set of standardized ontologies for both AEC and geospatial domains are needed (Lapierre and Cote 2007). The ontologies specify a set of classes, attributes, and relationships that provide meanings for the vocabulary used in the domain of knowledge. If we consider a "class" as a group of things with something(s) in common (e.g. concrete), then unified identifiers are used to identify things. Also, we need to provide useful information such as attributes and relationships (e.g. concrete has strength of 4000 PSI) about the things using standard formats. The standard data model that the semantic web infrastructure uses to represent this distributed web of data is called the RDF. "The concrete has strength of 4000 PSI" can be represented in RDF as this collection of triples; a subject donates “concrete”, a predicate donating “has strength of”, and an object donating “4000 PSI”. A subject (or an object) may be labeled with a URI, which is a universally unique identifier. In order to link our data to data from third parties via reuse of URIs and prevent the problem of co-reference, it is necessary to use only universally unique URIs.

Step 1: Conceptualization

Depending on the components and the level of detail, ontologies can be divided into upper, domain, and application ontologies. An upper ontology describes general concepts such as space, time, role, object, action, etc., which are applicable across a wide range of domains. BFO, Cyc, DOLCE, GFO, PROTON, Sowa’s ontology, and SUMO are among the most popular upper ontologies. Domain ontology is created with the aim of formalizing and representing shared concepts in a specific domain of interest (e.g. AEC). For instance, we can represent a rule about a specific role: A construction worker uses a tape measure to take a measurement; where “construction worker” is an instance of the concept worker, “tape measure” is an instance of the concept measuring tool, and “uses” and “take a measurement” are used to identify relations between these conceptual elements. The e-COGNOS (as well as many other examples mentioned earlier) is a good example of such ontologies. Application ontology is a representation of the semantics of a specific, focused application domain, which defines relevant concepts for a particular application (e.g. BIM or GIS). Given the increasing role of application ontologies in facilitating the integration of different types of information, this step examines how this level of ontology can be used to provide semantic interoperability between BIM and GIS operations. Previous attempts on the ontology development in the AEC have undoubtedly paved the way for seamless integration of building and construction related data, however, no application ontology exists for the building and construction domain that encompasses all IFC classes with different attributes. Thus, we construct a new ontology based on the EXPRESS schema. The focus is on IFC schema items such as attributes, classes, data types, individuals, and relations.

The semantic web community has shown increasing interest in adopting description logic as the paradigm formal system to represent the application domain in a structured way. Briefly, description logic models the application domain by defining the relevant concepts of the domain and then using these concepts to specify properties of objects and individuals occurring in the domain (Studer et al. 2007). Also, in simple terms, description logic describes the domain in terms of concepts, roles (such as relationships and properties) and individuals (or instances). For conceptual modeling, the proposed method organizes (or models) the building and construction concepts by using description logic definitions. There are two types of concepts: primitive concepts are used in this study to represent the natural classes of the IFC domain where only necessary conditions are specified and they can be recognized by their definition. Defined concepts are used to represent subclasses of the primitive ones (i.e. built using primitive concepts and properties). Thus, we define the IFC classes at the top of the hierarchical structure of the ontology as “primitive” concepts. For example, let us assume that an individual x is an instance of IfcWindow (as a primitive concept), thus x possesses the properties of IfcWindow such as “overall height” and “overall width”. The standard window, which is inserted into an opening and its profile represents a rectangle within the 2D plane of the opening, is defined by IfcWindowStandardCase. We define this IFC entity as a “defined concept”, so the associated properties of the IfcWindowStandardCase are necessary and sufficient. Again, let us assume that an individual y is an instance of IfcWindowStandardCase (as a defined concept), thus y possesses the properties of IfcWindowStandardCase and the y individual that possesses the set of the associated properties of IfcWindowStandardCase (e.g. inserted into an opening, and etc.) suffices to be inferred as an instance of the IfcWindowStandardCase.

For the purpose of forming the ontology, we define the IFC classes (or concepts in description logic) by their supertype entities and their relations with the other classes. Continuing with the above examples, IfcWindow can be defined as follows:

```
(defprimclass IfcWindow (?be IfcBuildingElement)
:=> (and (exists (?oh)
          (and (OverallHeight ?oh)
                    (>= (OverallHeight ?oh) 0)))
```

It defines a primitive concept IfcWindow which is a subtype of IfcBuildingElement. The keyword “defprimclass” is used to define the primitive concepts and introduce a set of necessary but not sufficient conditions. The above expression also states that all “IfcWindow” classes have at least one “OverallHeight” that is a positive measure, greater than zero. The defined concept “IfcWindowStandardCase” is defined as (defconcept IfcWindowStandardCase (?w IfcWindow)…), where "defconcept" creates named descriptions that describe sets or classes of objects.

Modern ontology languages such as OWL are based on description logics. As description logics describe the domain in terms of concepts, roles, and individuals, OWL describes that in terms of classes (instead of concepts), properties (instead of roles) and individuals. In particular, the formal specification of the OWL was influenced by description logics and its RDF/XML exchange syntax was influenced by a requirement for upwards compatibility with RDF (Horrocks et al. 2003). Thus, we use OWL ontologies to create the application ontology (hereafter referred to as the BIM ontology). The OWL axioms provide semantics about classes and properties by assigning necessary and/or sufficient characteristics to a class. The SubClassOf axiom represents subclass/superclass relationship, so since IfcWindow is a subclass of IfcBuildingElement, it necessarily inherits all characteristics of IfcBuildingElement, but not the other way around. The primitive concepts introduced by “defprimconcept” are translated to OWL with “subclassOf” axioms. The EquivalentClasses axiom states that two or more class expressions consist of the same set of individuals, so they are equivalent to each other and the subclass relationship is implied to go in both directions. Expressions using “defconcepts” in description logic correspond to the “equivalentClasses” in OWL.

For the purpose of arranging the IFC classes in a taxonomic (subclass–superclass) hierarchy, we define owl:Thing as the top class that contains individuals (things). In other words, all classes are rdfs:subclassOf owl:Thing. For each IFC element in EXPRESS, a corresponding OWL class is generated. Accordingly, the attributes and properties are converted into the appropriate OWL attributes and properties. We create a corresponding owl:Class in the ontology for each ENTITY definition in the EXPRESS schema. Furthermore, we define the IFC entities using a hierarchical entity structure, in which each entity is related with one other entity by subtype/supertype relationships. These “Subtype of” and “Supertype of” relationships are transformed into rdfs:SubClassOf and rdfs:SuperClassOf relations. URI references are also included in RDF/OWL models to describe subjects and objects. This study takes advantage of available URIs to annotate the EXPRESS entities and relations among them (Van Deursen 2010). The proposed methodology uses datatype properties to describe the relations between individuals and literal data (e.g. string, numbers, datatypes) and object properties to relate individuals to other individuals. For instance, the “CompositionType” property relates “IfcBuilding” to string values. We introduce “hasAttribute” property, which relates an “IfcBuilding” to a “CompositionType”. There are some properties that should be defined as an IFC entity. Thus, “rdfs:isDefinedBy” is used to state that a resource (e.g. BuildingAddress) is defined by an IFC entity (e.g. IfcPostalAddress). Step 3 describes how the IFC schema can be lifted onto an ontological level by using description logic and OWL syntax. A part of IFC ontology and its RDF graph is displayed in Figure 11.

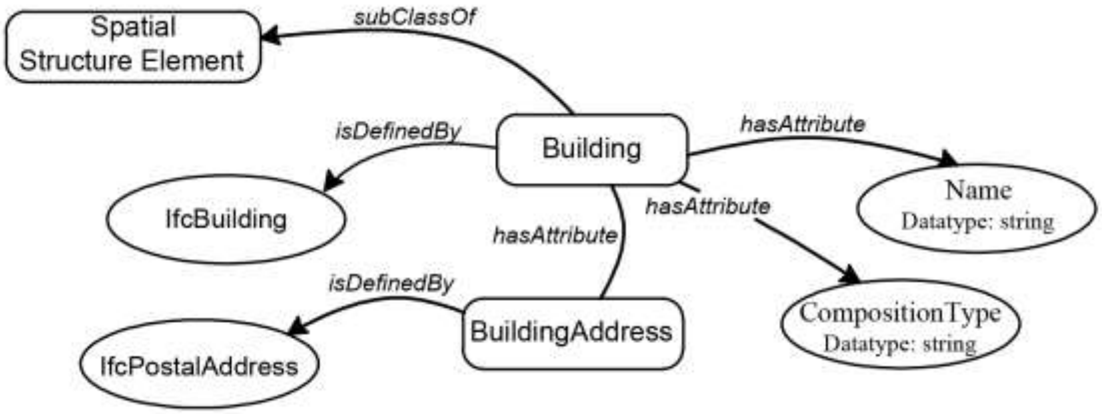


Figure 11: Representation of an EXPRESS entity (i.e. Building) as RDF graphs

Step 2: Integration

Ontology mapping is used in this step to identify semantically corresponding terms among BIM and GIS ontologies, e.g. which terms are semantically equal or similar. Although a complete discussion of various tools for mapping two ontologies is beyond the scope of this study, a brief description of the process is provided through an example. More details can be found in (Balachandar et al. 2013) and (Hu et al. 2005). Assume that we (as BIM users) want to integrate location and elevation information regarding existing conditions of jobsite terrain with the building's location on the site. The topographic data was extracted and manipulated using a GIS software product. Thus, in order to transform GIS or source ontology entities and instances into the BIM or target ontology, we adopt the graph structure approach to represent elements of the two ontologies in this study. As an example, Figure 12 shows the RDF graphs of GIS ontology adopted from the Center of Excellence for Geospatial Information Science (CEGIS) (USGS 2013) and BIM ontology, based on the IFC schema. These two different (but related) ontologies are expressed by RDF(s) and OWL.

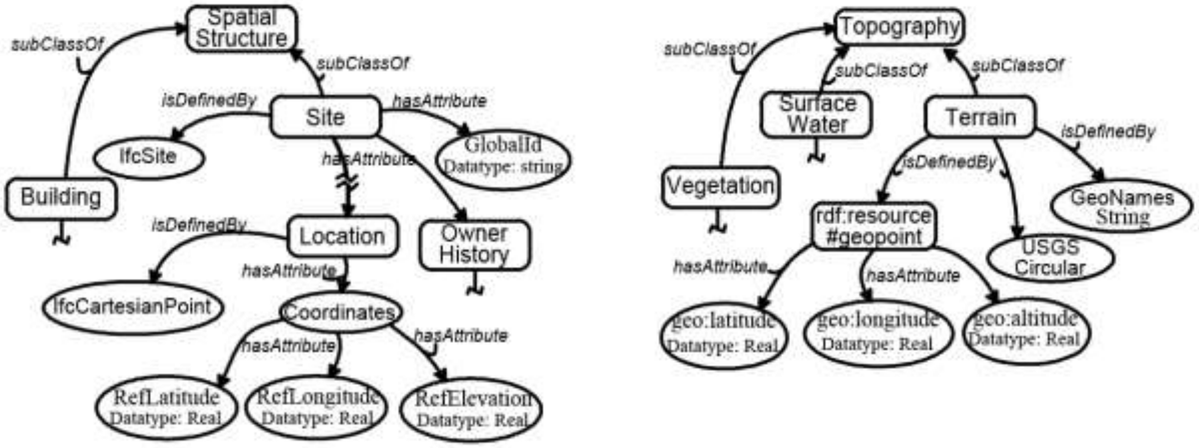


Figure 12: The RDF graphs of BIM (left) and GIS (right) ontologies

We compare the structures of entities of interest to quantify the degree of similarity of triples (subject, predicate, and object). By adopting Graph Matching for Ontologies (GMO) approach, it is able to measure the structural similarities between BIM and GIS ontologies. This ontology matching approach uses RDF bipartite graph model, which was first introduced by Hayes and Gutierrez (2004), to represent ontologies. Figure 13 shows the RDF bipartite graph of the GIS ontology, where property nodes are represented by circles, class statements are represented by rounded rectangular, and edge labels S, P, O indicate their subject, predicate and object.

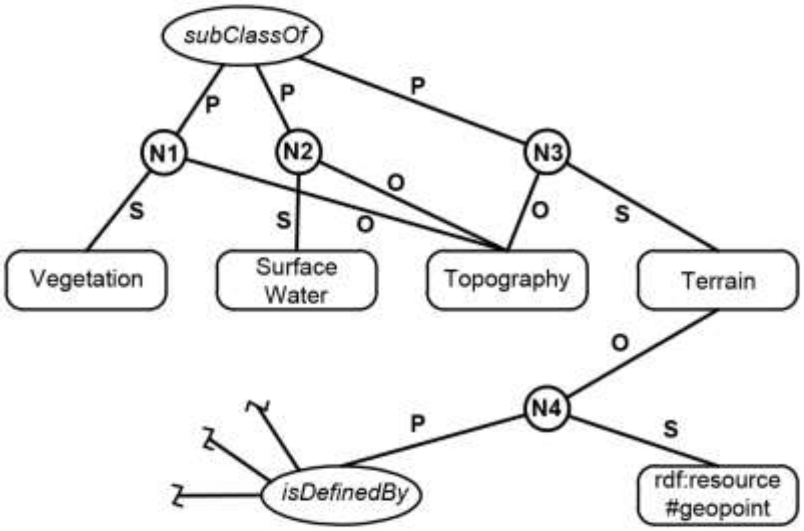


Figure 13: RDF bipartite graph of the GIS ontology example. Instance labels have been omitted for clarity

The adjacency matrix of the directed bipartite graph of ontology, denoted by A, has the following block structure:

$$A = \begin{pmatrix} 0 & 0 & A_{ES} \\ 0 & 0 & A_S \\ A_E & A_{OP} & 0 \end{pmatrix}$$

where AES is a matrix representing the connections from external entities (e.g. rdfs:subClassOf) to statements; AS is a matrix representing the connections from ontology entities (internal entities) to statements; AE is a matrix representing the connections from statements to external entities of the ontology; and AOP is a matrix representing the connections from statements to internal entities. In the example in Figure 12, the external entities include some common ones (e.g. rdfs:subClassOf, rdfs: isDefinedBy) used in two ontologies. However, If those entities are not used as subjects in the Ontology (as in Figure 12), A_{ES} is a zero matrix. The matrix representation of GIS ontology in Figure 12 is as follows:

$$\begin{array}{l|ccc|ccccc|cccc|}
\text{subClassOf} & & & & & & & & & & & & \\
\text{isDefinedBy} & & & & & & & & & & & & \\
\text{hasAttribute} & & & & & & & & & & & & \\
\cline{2-13}
\text{Vegetation} & & & & & & & & & 1 & 0 & 0 & 0 \\
\text{Surface Water} & & & & & & & & & 0 & 1 & 0 & 0 \\
\text{Topography} & & & & & & & & & 0 & 0 & 0 & 0 \\
\text{Terrain} & & & & & & & & & 0 & 0 & 1 & 0 \\
\text{\#Geo:Point} & & & & & & & & & 0 & 0 & 0 & 1 \\
\cline{2-13}
\text{N1} & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & & & & \\
\text{N2} & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & & & & \\
\text{N3} & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & & & & \\
\text{N4} & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & & & &
\end{array}$$

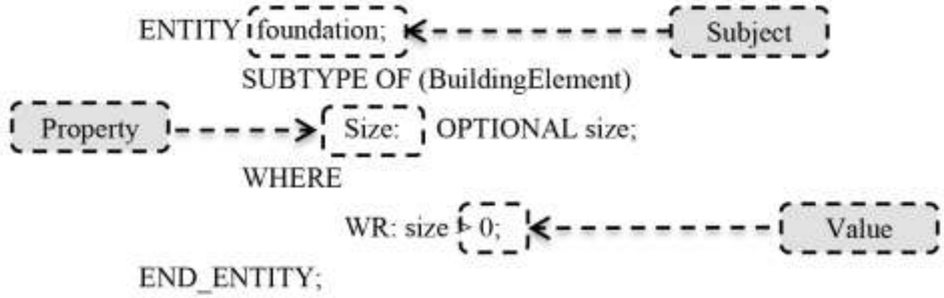
For the example in Figure 12, we classify the entities as properties (e.g. rdf:type and rdfs:subClassOf), classes (e.g. Terrain), and instances (e.g. individuals and data literals). Having similar classification (e.g. RefLatitude and geo:latitude are class entities) and role (e.g. subject or predicate) would also increase the chance of having similar relationship or concept. The built-in properties, datatypes, and URIs used in both ontologies should be taken into consideration when mapping between two domain ontologies. As such, any two identical URIs results in identical semantics. Now, it is possible to represent the similarity matrix of BIM ontology entities to GIS ontology entities and the external entities of GIS ontology to the external entities of BIM ontology. Based on the formulation in (Hu et al. 2005), the structural similarity matrix of BIM and GIS ontologies is created. Regarding the structural similarity between the given RDF graphs, we found the following entities to be similar concepts:

geopoint and CartesianPoint, GeoNames and GlobalId, geo:latitude and RefLatitude, geo:longitude and Ref Longitude, and geo:altitude and RefElevation.

The resulting ontology determines the relation as well as correspondences between BIM and GIS ontologies.

Step 3: Formalization

In this step, we translate building's elements and GIS data into the formal ontology languages, RDF/OWL. Since RDF is an excellent complement to XML in a way that provides a flexible way for the interchange of data between applications, it is better to convert BIM and GIS data to XML-like formats, such as IFC for building and GML for geospatial data formats. An EXPRESS entity of an IFC class is shown in Figure 14, in which “Subject” is used for the modeling of physical element such as foundation or building, “Property” is used to assign property to the subject (i.e. foundation) such as size, and “Value” or “Unit” is used to further specify the size property. GML defines features for physical entities (e.g. building, road) using simple properties such as names, integers, and Boolean values (true/false) and geometric properties such as Points, LineStrings, and Polygons. Because the original GML model was based on RDF, it contains many features of RDF, including the idea of representing information in “striped form” by asserting values of properties on objects so elements alternately represent nodes and edges.



```
ENTITY foundation;
    SUBTYPE OF (BuildingElement)
    Size: OPTIONAL size;
    WHERE
        WR: size > 0;
END_ENTITY;
```

Figure 14: EXPRESS entity example

The header of an IFC file states its name, description, translator version (if used) and schema version. The IFC entities and their attributes (both normal and optional) are specified in the body of the IFC file. Each IFC entity starts with a '#' character followed by a number. Since every individual in OWL needs a unique identifier, we will use these unique numbers to define the common instances or individuals of different classes. Each new IFC entity is defined after an equal sign, '=', and its attributes are represented by a set of comma separated values within parentheses. The normal attributes for the IFC entity always get non-null values, while the optional attributes may have null values indicated by a dollar sign.

Since all the buildings information (e.g. materials, quantities, representations, units, and etc) are defined as a set of IFC entities, we first define an OWL class named "Entity" for all IFC entity definitions (i.e. <owl:Class rdf:about="…Entity"/>). Then, we define the common supertypes of all other IFC entities as a subtype of this general class. The IFC entities such as "IfcAddress", "IfcMaterial", "IfcPerson", and "IfcRoot" are maximally general IFC classes at the same level of hierarchy. For example, IfcAddress is defined as follows:

```
<owl:Class rdf:about="...IfcAddress">
    <rdfs:subClassOf rdf:resource="...Entity"/>
</owl:Class>
```

This RDF data model represents a relationship (i.e. subClassOf) between a subject (i.e. IfcAddress) that is defined by "rdf:about" and an object (i.e. Entity) that is defined by “rdf:resource”. We continue with the subtype of each IFC class until no more IFC entity can be joined to the ontology. For instance, “IfcAddress” is the supertype of only two entities; “IfcPostalAddress” and “IfcTelecomAddress”, both have zero child nodes (i.e. there is no subtype entities in the ontology).

In order to perform the conversion between IFC and RDF/OWL documents, we divided the IFC attributes into three groups, according to their properties; (1) leaf node, (2) simple type, and (3) complex type. A leaf node attribute is an attribute of the IFC hierarchy/tree structure that has zero child nodes or attributes. The “value” is the only parameter required to define a leaf node attribute. For example, the IfcOrganization entity has five leaf node attributes; Id (optional), Name (normal), Description (optional), Roles (optional) and Addresses (optional). The values (e.g. Autodesk Revit as a string value) are the only parameters that we need to define these leaf node attributes. Thus, this IFC entity can be defined as #1= IFCORGANIZATION ($, 'Autodesk Revit 2014 (ENU)',$,$,$);. Regardless of the type of attributes, we represent each IFC entity as the subject of the RDF statement using an owl:Class and use “rdf:about” statement to describe that subject. Also, the rdfs:subClassOf property is used to state that one IFC entity is a subtype of another entity or resource. Consequently, every OWL class is a subclass of owl:Thing. The IfcOrganization entity is defined as follows:

```
<owl:Class rdf:about="..IfcOrganization">
  <rdfs:subClassOf rdf:resource="...IfcEntity"/>
</owl:Class>
```

We define a leaf node attribute as an OWL data type property because it relates literal data (e.g., strings, numbers, data types, etc.) to an IFC entity. The type of literal data is defined by “rdfs:range” and “rdfs:domain” is used to state that the leaf node attribute is an instance of the IFC entity. The “Name” attribute of the IfcOrganization entity is defined as follows:

```
<owl:DatatypeProperty rdf:about="...Name">
  <rdfs:domain rdf:resource="...IfcOrganization"/>
```

```
  <rdfs:range rdf:resource="&xsd;string"/>
</owl:DatatypeProperty>
```

Like XML, all the values for an OWL class should be written between its opening and closing angle brackets. If the string value for the “Name” attribute is “Autodesk Revit”, it should be declared like as follows:

```
<owl:NamedIndividual rdf:about="...Name">
  <...Name rdf:datatype="&xsd;string">Autodesk Revit 2014 (ENU)</...Name>
</owl:NamedIndividual>
```

A simple type attribute is defined by an IFC entity. In this way, the IFC entity acts as an attribute value. For instance, IfcApplication has one simple type attribute, ApplicationDeveloper, which is defined by IfcOrganization entity, and three leaf node attributes; Version, ApplicationFullName, and ApplicationIdentifier. In the OWL file, we use “rdfs:isDefinedBy” to represent the simple type attribute. Also, “rdfs:domain” is used to state that the simple type attribute is an instance of the IFC entity. The “ApplicationDeveloper” attribute of the IfcApplication is defined as follows;

```
 <owl:DatatypeProperty rdf:about="...ApplicationDeveloper">
  <rdfs:domain rdf:resource="...IfcApplication"/>
  <rdfs:isDefinedBy rdf:resource="...IfcOrganization"/>
</owl:DatatypeProperty>
```

There are some IFC entities such as IfcNormalisedRatioMeasure, IfcRatioMeasure, and IfcSpecularExponent that can be defined with single attribute and without any relation to another IFC entity. Therefore, we don’t define these distinct entities as an OWL class, instead they are defined an OWL data type property. Similar to the role of “rdfs: subClassOf” in forming the taxonomy of IFC classes, taxonomy of properties is formed by rdfs:subPropertyOf. Since the distinct IFC entities are used to specify an IFC attribute, we define them as “subPropertyOf” other IFC attributes. For instance, IfcMeasureWithUnit entity has two simple type attributes: ValueComponent defined by IfcRatioMeasure distinct entity and UnitComponent defined by IfcSIUnit entity. The “ValueComponent” attribute of the IfcMeasureWithUnit is defined as follows;

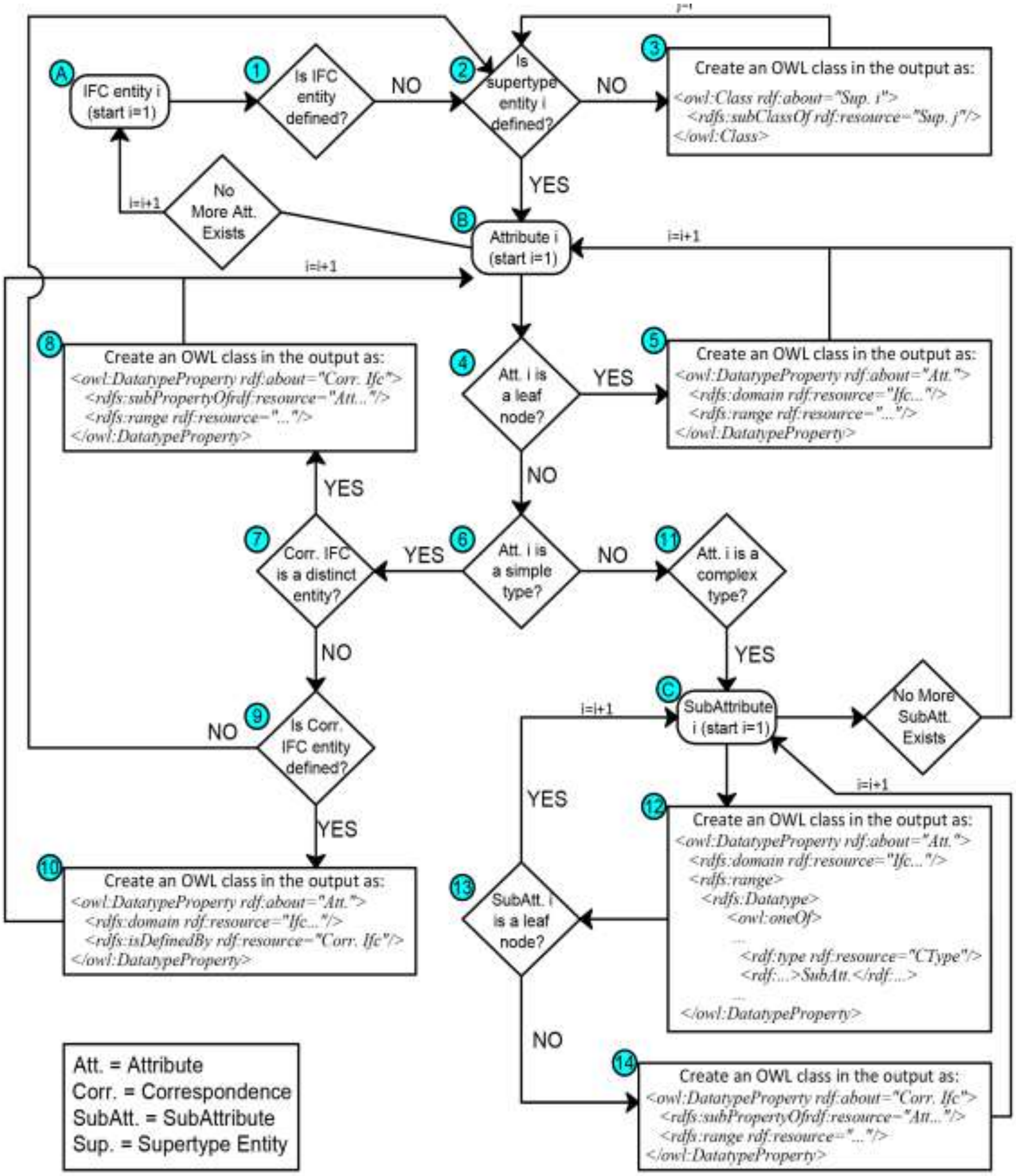
```
  <owl:DatatypeProperty rdf:about="...IfcRatioMeasure">
    <rdfs:subPropertyOf rdf:resource="...ValueComponent"/>
    <rdfs:range rdf:resource="&owl;real"/>
  </owl:DatatypeProperty>
```

A complex type attribute has one or more sub-attributes that describe the properties and values. In addition, the distinct list or ordered sequence of sub-attributes is declared by “Concept Type” or “C-Type”. For instance, IfcCartesianPoint has one complex type attribute, Coordinates, which is defined with a list of 1 to 3 sub-attributes (i.e. IfcLengthMeasure). To express this constraint, we define the concept type properties (e.g. list, range, and set) by property axioms, or more specifically range axioms. Thus, the range of values for the “Coordinate” attribute is limited to a list of first, second, and/or third IfcLengthMeasure sub-attributes. Additionally, these sub-attributes are defined either by distinct IFC entities or by a set of individuals. Again, we use “subPropertyOf” to define the distinct IFC classes. The “Coordinates” attribute of the IfcCartesianPoint is defined as follows;

```
<owl:DatatypeProperty rdf:about="...-Coordinates">
    <rdfs:domain rdf:resource="...IfcCartesianPoint"/>
    <rdfs:range>
      <rdfs:Datatype>
        <owl:oneOf>
          ...
            <rdf:type rdf:resource="&rdf;List"/>
            <rdf:first>pos=0</rdf:first>
            ...
        </owl:oneOf>
      </rdfs:Datatype>
    </rdfs:range>
  </owl:DatatypeProperty>
...
  <owl:DatatypeProperty rdf:about="...IfcLengthMeasure">
    <rdfs:subPropertyOf rdf:resource="...Coordinates"/>
```

```
    <rdfs:range rdf:resource="&owl;real"/>
</owl:DatatypeProperty>
```

Figure 15 shows the flowchart of IFC to RDF/OWL translation process for different types of IFC attributes. The above process continues until no more attribute exists for further translation as shown in Figure 15. An example of this transformation is shown in Figure 16, where an IFC element in EXPRESS schema is transformed into ontology format written in OWL. As shown in the EXPRESS data model in Figure 16, “Subject” is used for the modeling of a physical element such as building, “Property” is used to assign attribute (e.g. Name, CompositionType) to the subject (i.e. building), and “Value” or “Individual” is used to further specify the property’s value. At this stage, different ontology editor tools are used to edit and visualize ontology language and therefore donate how classes or entities are associated with others. Protégé is one of the oldest and most widely deployed ontology editing tools that is now widely used for RDF modeling. In this study, Protégé 4.3 is used for editing the BIM ontology. The W3C provided useful semantic web programs such as CWM that can be used for parsing the IFC files into RDF format. CWM is a general-purpose data processor for querying, checking, transforming and filtering information on the semantic web (W3C 2013).



```
<owl:Class rdf:about="Sup. i">
  <rdfs:subClassOf rdf:resource="Sup. j"/>
</owl:Class>
```

```
<owl:DatatypeProperty rdf:about="Att.">
  <rdfs:domain rdf:resource="Ifc..."/>
  <rdfs:range rdf:resource="..."/>
</owl:DatatypeProperty>
```

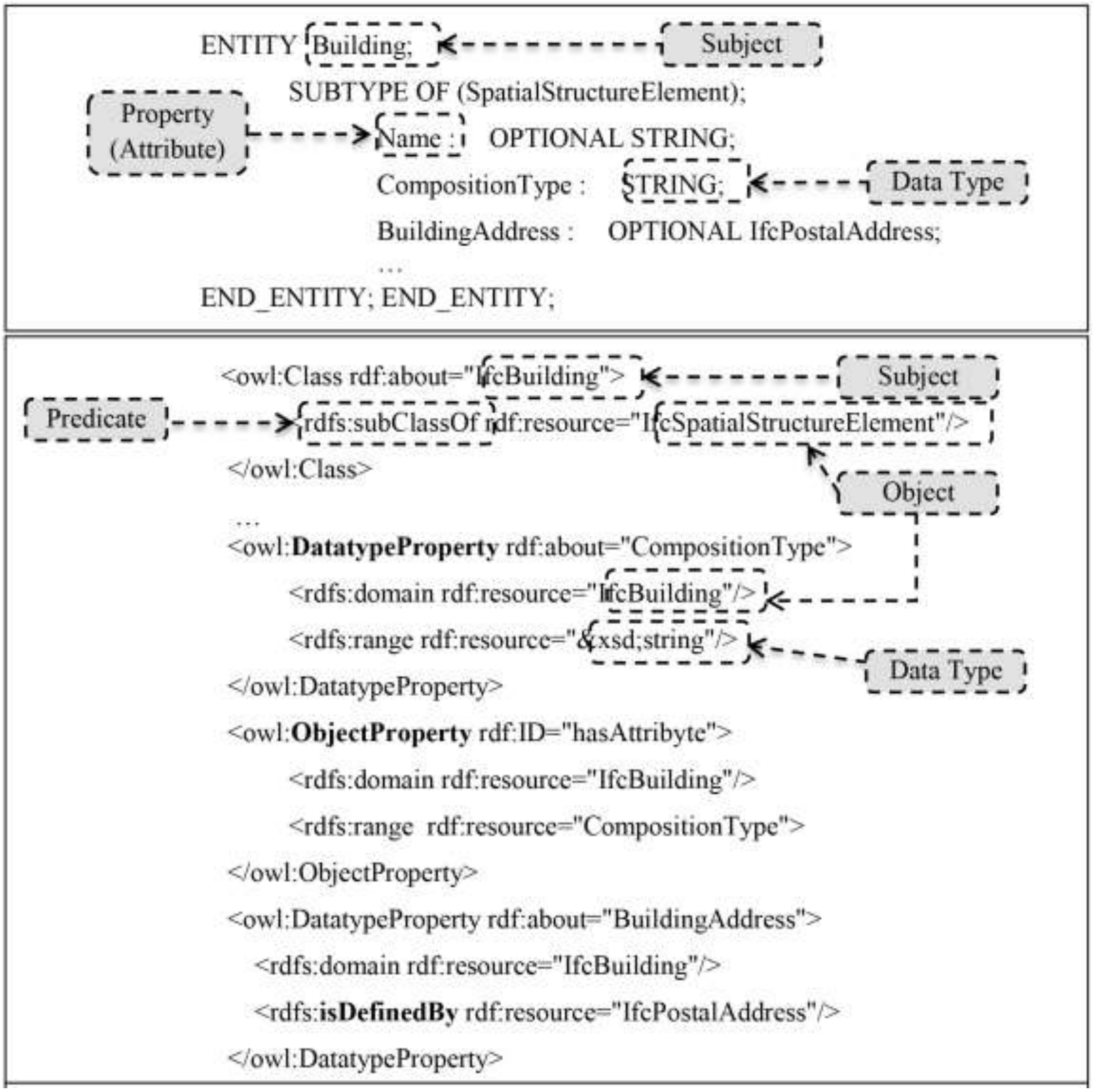
```
<owl:DatatypeProperty rdf:about="Corr. Ifc">
  <rdfs:subPropertyOfrdf:resource="Att..."/>
  <rdfs:range rdf:resource="..."/>
</owl:DatatypeProperty>
```

```
<owl:DatatypeProperty rdf:about="Att.">
  <rdfs:domain rdf:resource="Ifc..."/>
  <rdfs:isDefinedBy rdf:resource="Corr. Ifc"/>
</owl:DatatypeProperty>
```

```
<owl:DatatypeProperty rdf:about="Att.">
  <rdfs:domain rdf:resource="Ifc..."/>
  <rdfs:range>
   <rdfs:Datatype>
      <owl:oneOf>
      ...
       <rdf:type rdf:resource="CType"/>
       <rdf:...>SubAtt.</rdf:...>
      ...
 </owl:DatatypeProperty>
```

```
<owl:DatatypeProperty rdf:about="Corr. Ifc">
  <rdfs:subPropertyOfrdf:resource="Att..."/>
  <rdfs:range rdf:resource="..."/>
</owl:DatatypeProperty>
```

Figure 15: Process flowchart of IFC to RDF/OWL translation



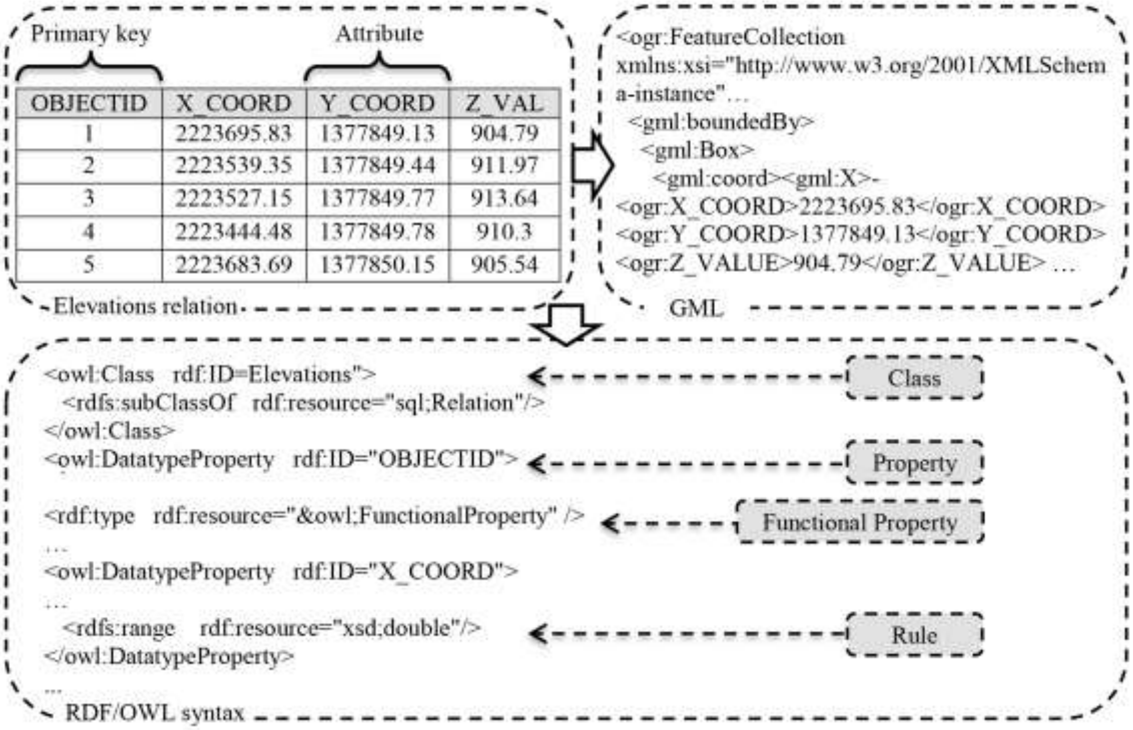
```
ENTITY Building;
    SUBTYPE OF (SpatialStructureElement);
        Name :    OPTIONAL STRING;
        CompositionType :    STRING;
        BuildingAddress :    OPTIONAL IfcPostalAddress;
        …
END_ENTITY; END_ENTITY;
```

```
<owl:Class rdf:about="IfcBuilding">
<rdfs:subClassOf rdf:resource="IfcSpatialStructureElement"/>
</owl:Class>
…
<owl:DatatypeProperty rdf:about="CompositionType">
      <rdfs:domain rdf:resource="IfcBuilding"/>
      <rdfs:range rdf:resource="&xsd;string"/>
</owl:DatatypeProperty>
<owl:ObjectProperty rdf:ID="hasAttribyte">
      <rdfs:domain rdf:resource="IfcBuilding"/>
      <rdfs:range  rdf:resource="CompositionType">
</owl:ObjectProperty>
<owl:DatatypeProperty rdf:about="BuildingAddress">
   <rdfs:domain rdf:resource="IfcBuilding"/>
   <rdfs:isDefinedBy rdf:resource="IfcPostalAddress"/>
</owl:DatatypeProperty>
```

Figure 16: EXPRESS entity (top) transformation into OWL ontology (bottom)

Most of the GISs are based on relational models that structure data according to tables of data, or relations. A GIS relational database is a set of relations (tables) containing a finite number of fields or attributes, but a semantic web agent uses description logic to represent predicates between different classes. The starting point to transform a GIS relational database into RDF is to define relational terminologies and identify their ontology equivalents. A relation (or a table) is organized into tuples (or rows) that have the same attributes (or columns). Each of the relations can be defined as a class (a group of things that share some properties). A class is stated as owl:Class (a subclass of rdf:Class) if the terms are not already present in the RDF schema. By this definition, all attributes associated with a relation can be represented as properties. As mentioned earlier, an RDF property states a relationship between subjects and objects (or between instances of a Class). Object type properties are used when stating relationships between instances of two classes. Otherwise, the relationships between instances of a class and values (e.g. number, string, and etc.) are defined using data type properties. Constraints are another important feature in a relational database. They allow us to restrict the possible values for a given attribute. For instance, a constraint can restrict an elevation attribute to values between 300 and 350 meter. Most of these constraints can be expressed by rules (or axioms) in RDF schema (e.g. SubClassOf, EquivalentClasses, DisjointClasses, and etc.).

In relational database terminology, a primary key of a relational table uniquely defines the characteristic of each tuple in the table. The primary key is represented as functional property axiom in this study, because a functional property can have only one (unique) value for each instance. The GIS data are extracted from the database using Quantum GIS, an open source GIS that supports GML and other data formats necessary for the data conversion process (GIS 2013). The conversion step makes use of an available Application Programming Interface (APIs), GeoTools, for the manipulation and parsing of GML data into RDF. The GeoTools is a Java API developed and maintained by the Open Source Geospatial Foundation which provides standards compliant methods for the manipulation of GIS data (GeoTools 2013). It should be noted that such tools only facilitate the exchange and manipulation of data, and the proposed method is independent of any specific software package. Figure 17 shows an example of such transformation where a relational database is first converted to GML and then interpreted.



OBJECTID	X_COORD	Y_COORD	Z_VAL
1	2223695.83	1377849.13	904.79
2	2223539.35	1377849.44	911.97
3	2223527.15	1377849.77	913.64
4	2223444.48	1377849.78	910.3
5	2223683.69	1377850.15	905.54

```
<ogr:FeatureCollection
xmlns:xsi="http://www.w3.org/2001/XMLSchem
a-instance"…
  <gml:boundedBy>
    <gml:Box>
      <gml:coord><gml:X>-
<ogr:X_COORD>2223695.83</ogr:X_COORD>
<ogr:Y_COORD>1377849.13</ogr:Y_COORD>
<ogr:Z_VALUE>904.79</ogr:Z_VALUE> …
```

```
<owl:Class   rdf:ID=Elevations">
  <rdfs:subClassOf   rdf:resource="sql;Relation"/>
</owl:Class>
<owl:DatatypeProperty   rdf:ID="OBJECTID">

<rdf:type   rdf:resource="&owl;FunctionalProperty" />
…
<owl:DatatypeProperty   rdf:ID="X_COORD">
…
  <rdfs:range    rdf:resource="xsd;double"/>
</owl:DatatypeProperty>
...
```

Figure 17: Relational database to ontology database transformation example

Step 4: Manipulation

This step aims to bridge the heterogeneity gap between semantic data available as OWL or RDF graphs and BIM tools by developing an interoperable framework that translates SPARQL queries to semantically equivalent IFC entities. In addition to syntax and structure, there might be major differences in meaning (or semantics) between RDF or OWL data and IFC data models. Therefore, decision makers need to have domain knowledge and be able to interpret the semantics from the data provider in order to use them in a BIM environment. For instance, two schemas may contain a “Vegetation” object, but the data provider’s definition of “Vegetation” can be different from its meaning in the target schema (e.g. IFC schema). In addition to the concepts with similar name but different meaning, they may have the similar meaning but different names such as Elevation and Altitude. In many cases, semantics used by the data providers do not necessarily match those used by BIM tools. To achieve this, we define a set of mappings between OWL/RDF ontologies and the IFC EXPRESS schema in order to transform the original SPARQL query results to a set of outputs which are semantically meaningful in terms of the BIM application.

Perhaps the most readable format for the SPARQL query results that is compatible with the BIM tools is XML. This step adopts the concept of integrity constraints in the query translation technique to guarantee consistency of data during query processing and return correct results to BIM users. For instance, a “PRIMARY key” constraint is represented as functional property axiom, because a functional property can have only one (unique) value for each instance. A NOT NULL constraint is used to ensure that an ifcXML entity cannot have NULL value for normal attributes. A UNIQUE Constraint is used to ensure that all property’s values (or individuals) are different.

A SPARQL query consists of a set of triples like RDF triples except that each of the subject, predicate and object may be a variable. A typical SPARQL query looks something like “select DISTINCT ?subject ?property ?value WHERE {?subject rdfs:subClassOf SpatialStructureElement. ?subject ?property ?value.}. This query would return the property and value components of subjects defined as subclass of SpatialStructureElement class in the dataset. A SPARQL query’s WHERE clause describes the data to pull out of a dataset, and the URIs in RDF triples are necessary to identify which data to retrieve. The DISTINCT keyword prevents the SPARQL processor from showing duplicate answers. Other SPARQL query keyworks, such as CONSTRUCT, FILTER, and OPTIONAL may also be used for giving the query the flexibility to retrieve data that may or may not match every single triple pattern. In this section, a description of the process developed for converting the query results from SPARQL into ifcXML is provided.

Regardless of the form in which query results may be presented, an ifcXML document shall contain header information and pre-defined information structure (e.g. unit(s) of serialization, EXPRESS entities and attributes for the ifcXML documents, etc.).

Thus, we define a single root element (i.e. <ifc:uos…>) at the top level of an ifcXML document that contains other elements. This root element defines the XML namespace, schema and other configurations. Each element should be written between its opening and closing angle brackets, marking the beginning and ending of the element. For instance, IfcOrganization that is defined by a “Name” attribute (as a normal attribute) should be written as <IfcOrganization> <Name>…</Name> </IfcOrganization>. XML elements can have attributes that provide additional information about the elements. Each of the XML attributes can be defined as a Property in an IFC document. However, IFC attributes are represented as elements in XML. Thus, <Name> element in the above example is an attribute for the IfcOrganization entity. One way to differentiate an entity and its attributes in the ifcXML is to assign a unique identifier code to the XML element. This is done by using an id attribute. An attribute has a label and a value in quotes. Therefore, the IfcOrganization entity can be represented as <IfcOrganization id="…"> <Name>…</Name> </IfcOrganization>. It is possible to reference another element that is declared elsewhere by using a ref or href attribute. In this case, the element should also have the xsi:nil=”true” attribute to show that the element does not have any content (e.g. <IfcOrganization xsi:nil="true" ref="…"/>). Any id value referenced by a ref (or even href) attribute should exist in the same document. All the values for an IFC entity should be declared as the XML element’s content. If the string value for the Name attribute is “Autodesk Revit”, it should be declared like <Name>Autodesk Revit</Name>. Figure 18 shows the flowchart of data conversion process for different types of IFC attributes. The application of this process is illustrated in the following use case example. For the purposes of simplicity and because of limited space, many of the optional attributes have been excluded from the example.

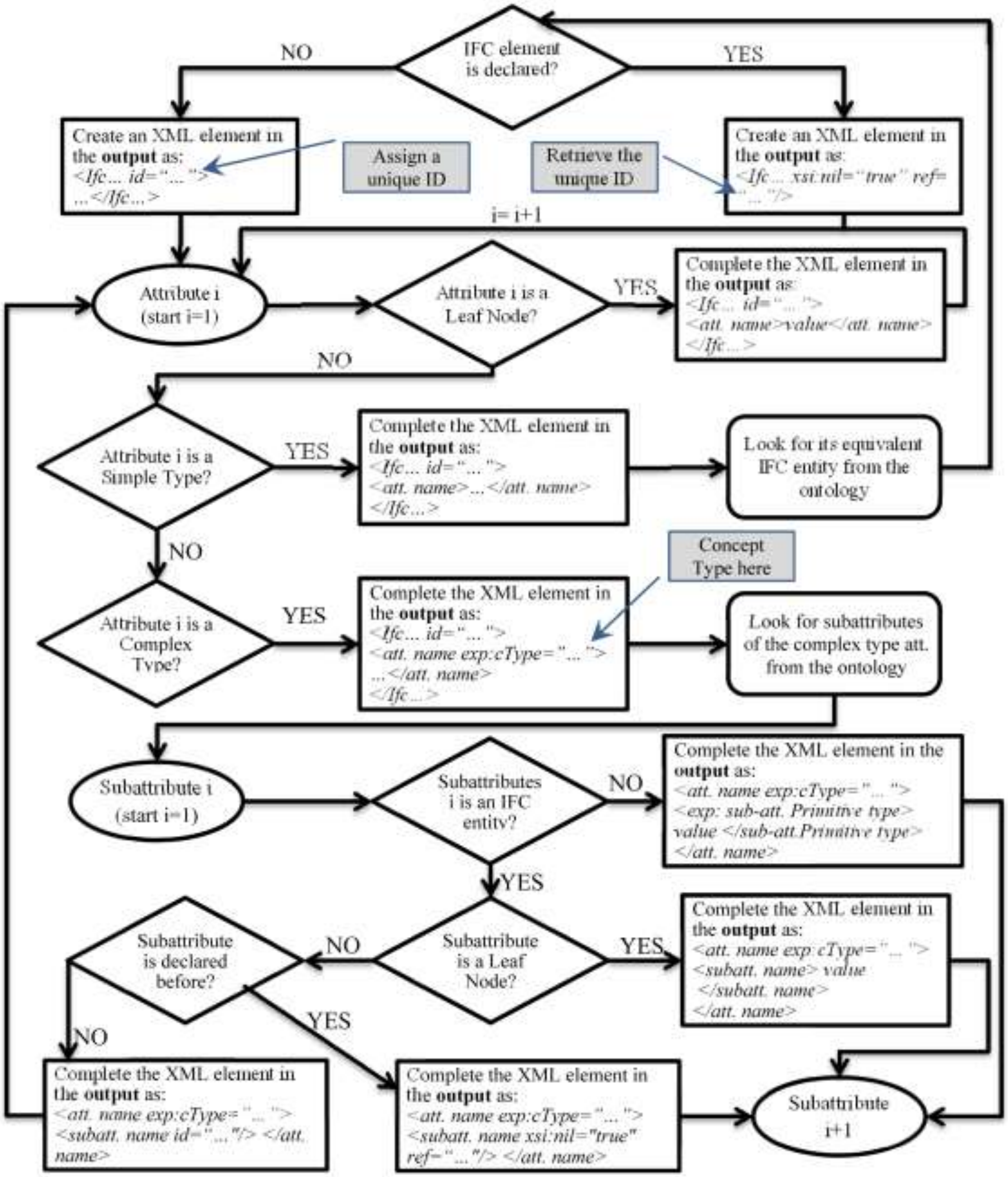


Figure 18: Process flowchart of XML to ifcXML data conversion

A central aspect of query processing is the specification of the relationship between the source data and the destination system (e.g. BIM tools) schema (so-called mapping). Once an equivalent IFC entity is specified, its required attributes and related entities are added to a predefined container structure including header information and unit(s) of serialization. Then, each set of query results is converted into the XML equivalent to the EXPRESS based specification, called ifcXML. A mapping process between the XML query results and the ifcXML data structure is designed and documented. The proposed mapping model specifies the relationships between XML and ifcXML data models in a computer interpretable form.

Table 2 shows the query results in XML formats and their equivalent ifcXML entities. Entity IFCPerson has two leaf node attributes (FamilyName and GivenName) and it is not declared. Thus, we create an XML element in the output as <IfcPerson id="i1000"> …</IfcPerson>. Since the entity is not previously declared, it is given a unique identifier (i.e. id="i1000"). The conversion process starts with the first attribute (i.e. FamilyName) that is a leaf node attribute. Therefore, we complete the XML element in the output as <IfcPerson id="i1000"> <FamilyName> Karan </FamilyName> </IfcPerson>, where "FamilyName" is the attribute name and "Karan" is the attribute value. Entity IFCPerson can be specified once this process is repeated for all attributes. Although not shown in Table 2, the GivenName attribute can be similarly converted and added to the IFCPerson entity.

Entity IfcPersonAndOrganization has two simple type attributes (ThePerson is defined by IFCPerson and TheOrganization is defined by IfcOrganization) and it is not declared elsewhere. Thus, we create an XML element in the output as <IfcPersonAndOrganization id="i1100"> …</ IfcPersonAndOrganization>. Since the entity is not declared before, it is given a unique identifier (i.e. id="i1100"). The conversion process starts with the first attribute (i.e. ThePerson) that is a simple type attribute. Therefore, we complete the XML element in the output as <IfcPersonAndOrganization id="i1100"> <ThePerson> … </ThePerson> </ IfcPersonAnd-Organization>, where ThePerson is the attribute name. Entity IFCPerson is already declared, so the previously declared id is returned (i.e. <IfcPerson xsi:nil="true" ref="i1000"/>). Although not shown in Table 2, the TheOrganization attribute can be similarly converted and added to the IfcPersonAndOrganization entity. The only difference is that, in the TheOrganization attribute, the IfcOrganization entity and its two leaf node attributes (i.e. Name and Description) should be defined within the TheOrganization attribute itself as they are not declared previously.

Entity IfcDirection has one complex type attributes, DirectionRatios, which is defined with a list of 2 to 3 sub-attributes. Since the IFC entity is not declared elsewhere, we create an XML element in the output as <IfcDirection id="i1200"> …</IfcDirection> and assign a unique identifier (i.e. id="i1200"). The DirectionRatios attribute is a complex type attribute with Concept Type (cType) of list, so we fill the XML element in the output as <IfcDirection id="i1200"> <DirectionRatios exp:cType="list"> ... </DirectionRatios> </IfcDirection>. It has two sub-attributes, none of them are IFC entity and their primitive type is "double". Therefore, we complete the XML element in the output as <IfcDirection id="i1200"> <DirectionRatios exp:cType="list"> <exp:double pos="0">6.12E-17</exp:double> <exp:double pos="1">1. </exp:double> </Direction-Ratios> </IfcDirection>, where double is the sub-attribute primitive type and 6.12E-17 (or 1.) is the sub-attribute value. Also, each sub-attribute may have a position attribute. As explained earlier, IfcCartesianPoint is another example of an IFC entity with a complex type attribute that can be similarly converted and added to the ifcXML output. The only difference is that, in the Coordinates attribute, the sub-attributes are lead node attributes defined by IfcLengthMeasure entity. The resulted ifcXML documents must be validated with an XML schema validating parser. Thus, all the syntactic mistakes and missing elements or improper order of elements can be corrected.

Table 2: Query results in XML formats and their equivalent ifcXML entities

Query Results in XML Format

```
<result>
    <binding name="value">
        <literal>Karan</literal>
    </binding>
    <binding name="subject">
        <literal>FamilyName</literal>
    </binding>
    <binding name="predicate">
        <literal>rdfs:domain</literal>
    </binding>
    <binding name="object">
        <uri>…#IfcPerson</uri>
    </binding>
</result>
```

ifcXML Output

```
<IfcPerson  id="i1000">
      <FamilyName>Karan</FamilyName>
      <GivenName>Ebrahim</GivenName>
</IfcPerson>
```

Query Results in XML Format

```
   …
    <binding name="subject">
        <literal>ThePerson</literal>
    </binding>
    <binding name="predicate">
        <literal>rdfs:domain</literal>
    </binding>
    <binding name="object">
     <uri>…#IfcPersonAndOrganization</uri>
    …
    <binding name="subject">
        <literal>ThePerson</literal>
     …
        <literal>rdfs:isDefinedBy</literal>
     …
        <uri>…#IfcPerson</uri>
…
```

ifcXML Output

```
<IfcPersonAndOrganization id="i1100">
   <ThePerson>
       <IfcPerson xsi:nil="true" ref="i1000"/>
    </ThePerson>
    <TheOrganization>
       <IfcOrganization id="i1050">
           <Name>Autodesk Revit… </Name>
           <Description></Description>
       </IfcOrganization>
     </TheOrganization>
</IfcPersonAndOrganization>
```

Query Results in XML Format

```
<result>
    <binding name="value">
        <literal> 6.12E-17</literal>
    </binding>
    …
    <binding name="predicate">
        <literal>rdfs:subPropertyOf</literal>
    </binding>
    <binding name="object">
        <literal> DirectionRatios</literal>
    </binding>
</result>
…
```

ifcXML Output

```
<IfcDirection id="i1200">
    <DirectionRatios exp:cType="list">
      <exp:double pos="0">6.12E-
                          17</exp:double>
      <exp:double pos="1">1.</exp:double>
    </DirectionRatios>
</IfcDirection>
```

Step 5: Evaluation

Through two use case examples and a case study, the potential usefulness of the proposed methodology will be validated. Development of construction site topography using GIS and then modeling that in a BIM environment, and modeling of temporary facilities using BIM and locating them in a GIS environment are two use case examples that are utilized in this study. Moreover, the aforementioned procedure is employed for monitoring construction supply chain management of a building project. Details are provided in the next chapter.

CHAPTER V

VALIDATION

Considering the large number of applications and the nature of the information in the BIM and GIS domains, two use case examples as well as a case study are utilized for the validation purpose: (1) development of construction site topography using GIS and then modeling that in a BIM environment, and (2) modeling of temporary facilities using BIM and locating them in a GIS environment. In the first use case example, geospatial analyses are used to retrieve height information about a construction site topography and then to generate a geo-referenced dataset. In the second use case example, we model a tower crane (as a temporary facility) using BIM and then identify its optimal location in a GIS environment. The application of the proposed method is not limited to these examples, and many other interoperability problems in BIM-GIS integration can be approached by the steps explained in this study (e.g. make material supplier’s information available and understandable to contractors through semantic web services).

Use Case Examples

Figure 19 shows the overall system architecture for developing a digital model of construction site topography using GIS, followed by modeling of temporary facilities using BIM and finally locating them in a GIS environment. The digital model of the construction site terrain is currently being used in several application areas such as volumetric calculations in cut-and-fill problems, route planning of vehicles for earthmoving projects, visualization of construction operations, and site layout planning. Digital elevation models (DEMs) can be acquired through terrestrial methods (e.g. ground surveying) and remotely sensed data (e.g. satellite images, airborne LiDAR, and etc.).

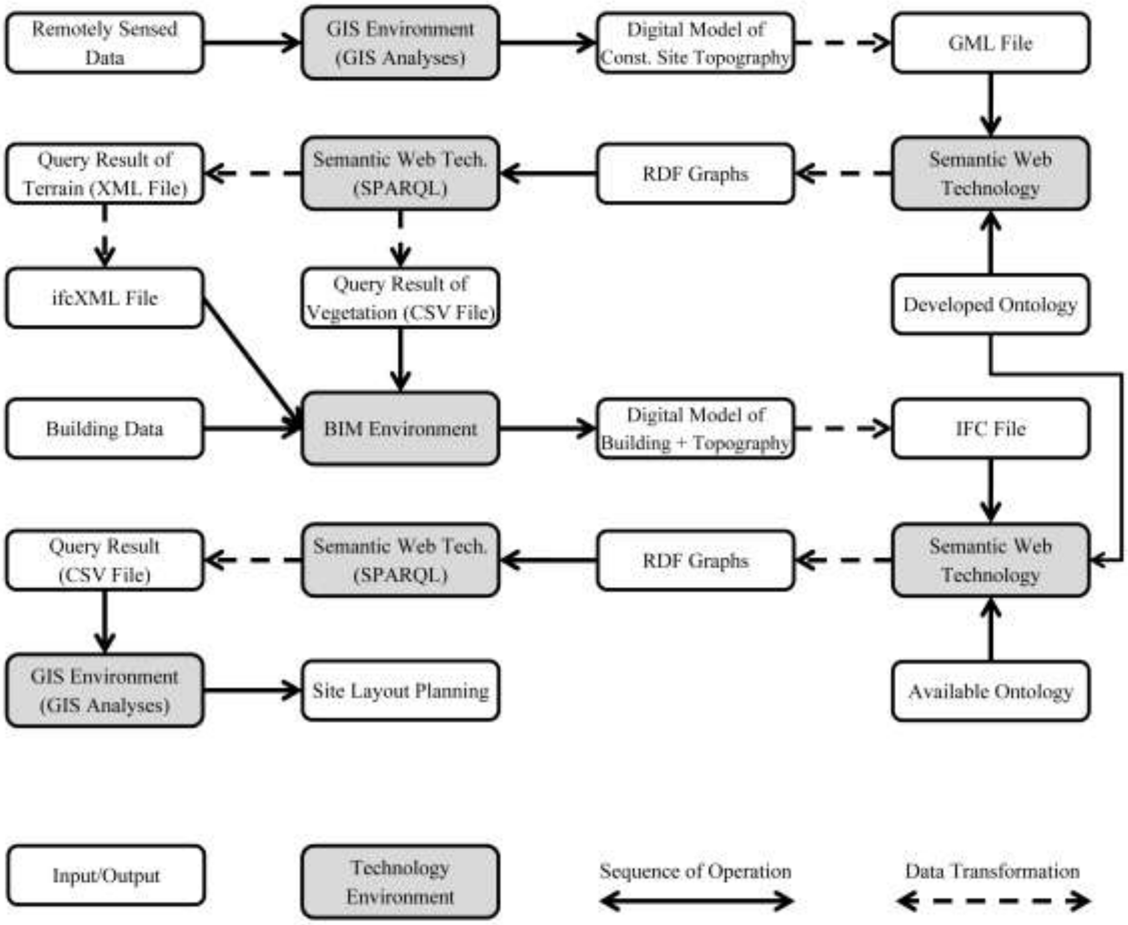


Figure 19: BIM and GIS integration for preconstruction operations using semantic web services

To retrieve height information about the construction site topography, we followed a similar approach as Karan et al. (2013), in which GIS analyses are used to generate a geo-referenced model of the existing conditions of the construction site terrain. The study area is located northwest of Atlanta, Georgia, with an area of 51,270 m2 (12.67 acres), and with average elevation of 284 meter (933 feet). The site is covered with light vegetation and is surrounded on three sides by roads and on one side (i.e. south) by railroad tracks. Because there is no standardized format to exchange data between different BIM and GIS software, the precise meaning of the topographic data is not understood by the BIM platform. In the GIS environment, we developed the DEM as a raster model. In order to transform its relational database into RDF/OWL, we annotate the properties of the raster model such as the cell size, class type, the number of rows and columns, and the coordinates of its origin. The elevation data are extracted from the relational database and transformed into GML. The conversion step makes use of an available API, GeoTools, for the manipulation and parsing of GML data into RDF/OWL. It should be noted that the available APIs only provide part of the adaptation required for the conversion of GML files into RDF triples (e.g. interfaces for basic RDF entities). The ontology (as described in the research methodology section) is needed to define the classes and their association. According to the developed ontology, we define bare ground, vegetation, and body of water as different classes of topography in this study. After writing and editing the ontology in a machine-processable ontology language, the syntax of the RDF models was validated using the RDF validation service at www.w3.org/RDF/Validator. Although the lightweight ontology was carefully verified and validated using the ontology editor tool, the results of the query need to be used to ensure its quality and conformance to standards. That is, we should be able to verify and validate the models based on the query output in the BIM environment.

The Jena ARQ, which is a query engine for Jena that supports the SPARQL RDF Query language, is used to retrieve the data required for surface modeling from the related RDF file (ARQ 2011). Jena is an open source Java framework for building semantic web applications. To create BIM topographical models of the existing construction site, the related parameters such as the classes used in the data, latitude/longitude properties, physical quantities, axioms and other annotations defined in the data are obtained through query (e.g. SELECT DISTINCT ?class WHERE {?class rdfs:subClassOf Bare Ground}). As described earlier, the site topography is modeled as a raster map that contains regular grid cells (which uniquely defined by latitude, longitude) and elevation values assigned to each cell. Depending on the type of class, a grid cell might have two elevation values; altitude for all elements in the Terrain class and height for the Vegetation class. Considering that many BIM software tools like Graphisoft ArchiCAD and Autodesk Revit support CSV input, this format is used to express the results of SPARQL queries for bare ground and body of water classes. To generate the topography model, a CSV file with x, y, and z-coordinate of each recorded topography point is used as the output of SPAQRL queries. Using the geometries in the CSV format, a terrain model is created as TIN surfaces in the BIM environment.

However, it is not easy to directly transfer the results of SPARQL queries for vegetation class. In this study, the XML format is used to return the results of SPARQL queries to the building model. Currently, an XML document is not supported by BIM authoring tools, thus we applied our proposed conversion methodology to transform the results to an XML representation of IFC data, ifcXML (e.g. substitutionGroup as the semantic relation SubClassOf). Table 3 indicates the mapping between a small portion of the XML results and an ifcXML schema. In certain cases, some additional components might be missing within the XML code since the RDF file might not be detailed enough. The equivalent IFC entity (e.g. ifcSite) is probably the most obvious and also the most important part that may be specified by the user. In addition, a predefined container structure including header information, unit(s) of serialization, and mapping of EXPRESS entities and attributes for the ifcXML documents is defined and used to translate and fill all query results into an ifcXML document corresponding to the given IFC entity. For the vegetation class, we make use of the SPARQL “CONSTRUCT” query form to create new graphs and to represent a vegetation element itself (equal to xs: element in ifcXML) and a neighboring bare ground sharing common latitude and longitude values as its host. In other words, we define an explicit dependency between each vegetation element and a host element where we can place the vegetation element. To generate the topography model, all elements in the Terrain class must first be placed in BIM and then the Vegetation class can be imported.

Table 3: Translation of a small portion of query results in XML format (use case example)

Original XML format	**ifcXML schema**
<variable name="Vegetation" /> …	<xs:element name="Vegetation" /> …
<rdfs:subClassOf …>	substitutionGroup= …
…	type="ifc:IfcElementCompositionEnum" …
<variable name="host" /> …	</xs:element>
<variable name=" geo: latitude " /> …	<xs:element name="IfcObjectPlacement" …type…
<variable name=" geo: longtitude " />	<xs:attribute name="RefLatitude" …type…
…	<xs:attribute name="RefLongitude" …type…
<variable name=" height " /> …	<xs:attribute name="RefElevation" …type…
…	…

Having developed the construction site topography in the BIM environment, the next step is to model temporary facilities and integrate the site model and the building together into a single environment. The building's spatial geometry as well as the material being used is defined at this stage. To locate tower cranes, as an example of temporary facilities, in a GIS environment we represented the locations of supply (loading) and demand (unloading) points by the centroid of an area where the material components are assigned. In this study, Autodesk® Revit Architecture 2013 was used to develop the building model. IFC is used as the data repository for addressing geometry, relations and attributes of the BIM model. In the use case example, the proposed methodology is applied to convert the IFC file to RDF format. The generated RDF file is imported into the ontology editor environment. Consequently the available ontology is evaluated and revised. The geometry of each object in EXPRESS is represented by a set of comma separated values within parentheses after the name of the object. In order to accurately represent the building elements within GIS context, spatial coordinates is transformed from local coordinate systems to the real word coordinate system (i.e. georeferenced) with the aid of a coordinate transformation matrix. The axes of the local coordinate system are rotated compared to the axes of the real world system and the origin of the local coordinate system is located at the origin of the real world system. For each subject definition in the EXPRESS schema a corresponding rdf:datatype is created as a subclass of rdfs:Class. For instance, “IFCFooting(…,'Footing-Rectangular:4 x 4 x 1...)” is transformed as “rdf:datatype="http://www-.w3.org/2001/XMLSchema#string"-> Footing -Rectangular:4 x 4 x 1…”.

For the purpose of determining the geometric layout of supply and demand points with their maximum load, SPARQL is used to issue queries based on the RDF such as “select Class: ifc:IfcBuildingStorey to get all the concrete slabs located in a given story”, “select Class: ifc:IfcLocalPlacement to determine the local coordinate system of a given slab”, and “select Class: ifc:IfcQuantityWeight to get the total weight of the slab”. Considering that CSV is one of the several table formats that GIS software can read, the results of SPARQL queries for locating tower crane is expressed as CSV format that has x, y, and z-coordinate representation of each supply and demand point. This CSV file became the input to the GIS software, ESRI® ArcGIS. The file contains more than 150 supply and demand points, posted in World Geodetic System (WGS) datum. Considering the lifting capacity of each crane, feasible areas for locating the tower cranes are categorized under the criterion of minimized possibility of conflicts between tower cranes and other facilities. Figure 20 shows the four steps of modeling the topography and the building in a graphical way. The aim of these two use case examples is to demonstrate the feasibility of using semantic web techniques for transform preconstruction-related information back and forth between BIM and GIS modelling environments.

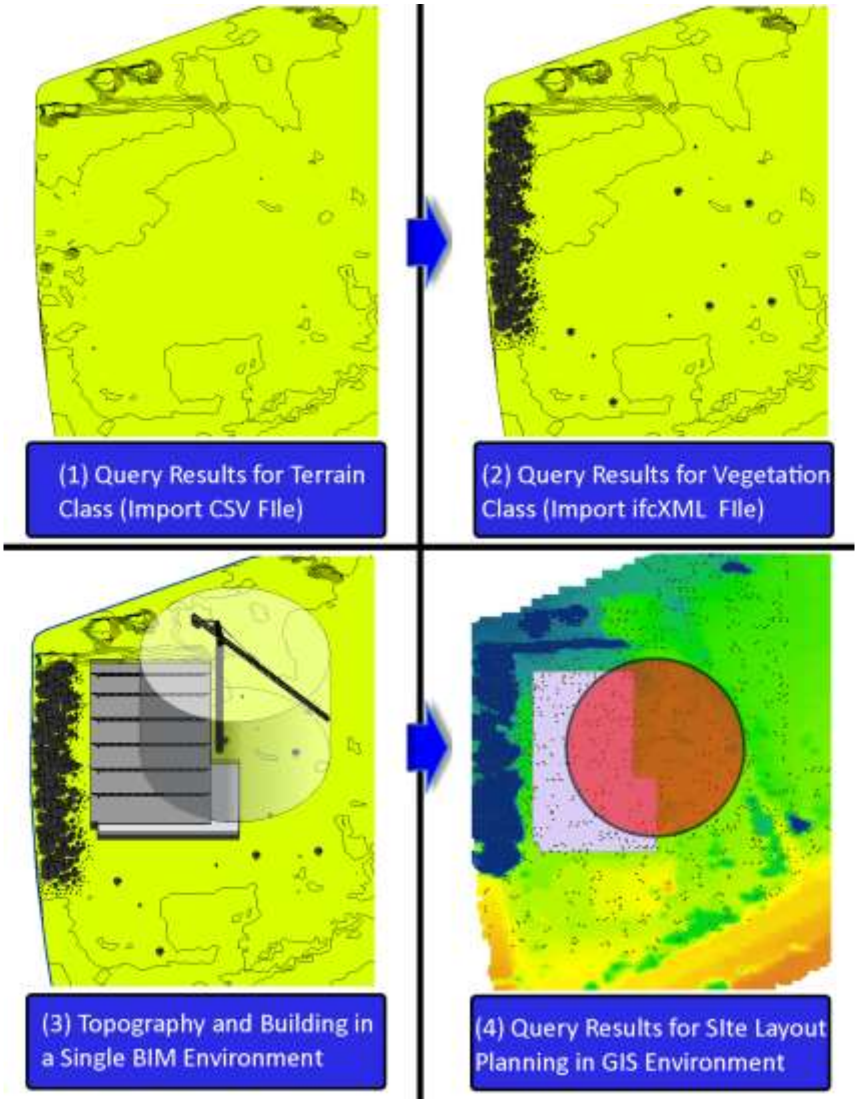


Figure 20: Four process steps and corresponding outputs in use case examples

A closer look at the construction industry shows that a considerable amount of waste produced is rooted in poor management of the material supply chain (e.g. delivery services, inventory, communications). Various IT models have been used in the literature as a way to improve the integration process of supply chain management for construction materials. CSCM is an application area where both BIM and GIS can play a key role in improving process efficiency. An integrated GIS-BIM model was presented in an earlier study (Irizarry et al. 2013) manifesting the flow of materials, availability of resources, and "map" of the respective supply chains visually. As claimed by the authors, the proposed system suffers from a lack of sematic interoperability across the GIS and BIM domains and it requires the user to have knowledge about both systems and their functionalities. For example, after importing an IFC file to GIS, the user needs to know how BIM information is represented in the GIS model. Although a central Microsoft Access database was used for transferring attribute data between BIM and GIS, this approach is inefficient and lacks semantic interoperability. In this section, the same case study is considered to show the benefits gained from the use of semantic interoperability. The main focus of this case study is on the procurement phase of a project in which information pertaining to the location of supply chain assets is visually monitored. While some steps of the case study are performed either in BIM or in GIS itself, material and component data is exchanged frequently between these two technologies. In addition to this high level of integration, using the same case study as the baseline for comparison is another reason for choosing the CSCM application as the validation approach to evaluate the benefits of the proposed methodology.

The methodology is employed for monitoring CSCM of a building project in Carrollton, Georgia, “The School of Nursing at the University of West Georgia”. The project involved a three-story, 65,000 square foot building accommodating all functions for nursing education and support spaces. The facility will house a variety of instructional spaces, including a 135-seat auditorium, 65-seat tiered classroom, computer classroom and lab, and flexible classrooms, as well as administrative and faculty support spaces. We use BIM capability to accurately provide a detailed takeoff in an early phase of the procurement process and GIS to support the wide range of spatial analysis used in the logistics perspective (warehousing and transportation) of the CSCM. To evaluate logistics constraints involved in the material delivery process, GIS is used to map the entire supply chain process, e.g., location of suppliers, transportation, value adding, and nonvalue adding activities. As shown in Figure 21, the CSCM workflow is described as follows: (1) using different types of elements (e.g. walls, columns, doors…), the availability of materials are evaluated in the pre-design phase. (2) Sourcing refers to the process of finding suppliers of goods and the impact of supplier's location on cost and schedules for a given construction project (3) Logistics is the management of the flow of materials between the suppliers to the construction site in order to meet the requirements of a given project. Logistics involves the integration of information, transportation, inventory, warehousing, and material handling. (4) Performance Management provides visibility into key performance indicators (KPIs) across the supply chain. And (5) monitoring and inspection deal with available and accurate information concerning the status of material at different stages within the construction supply. The overview of CSCM information flow in the case study, which was used in the earlier study, is shown in Figure 22. In the following sub-sections, different stages of the model are explained.

Case Study Step 1 — BIM Module: define building elements and properties

The building's elements are defined at this stage, and the type of each element is determined based on the material being used. The required amount of building information (i.e. 3D geometric representations and related semantic information) is provided as an IFC file. Depending on the type of building materials, the supply chain process could be engineered-to-order (ETO), made-to-order (MTO), assembled-to-order (ATO), and made-to-stock (MTS) products. Because each of these four general types of construction products has its own supply chain, we define the relevant parameters for each type.

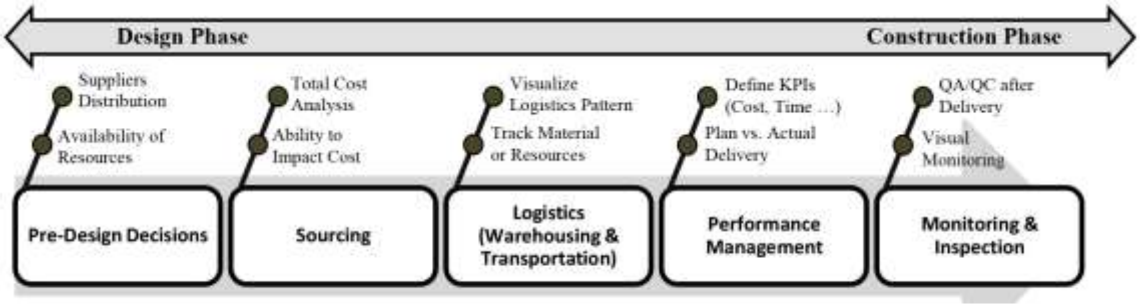


Figure 21: Construction supply chain framework in the case study

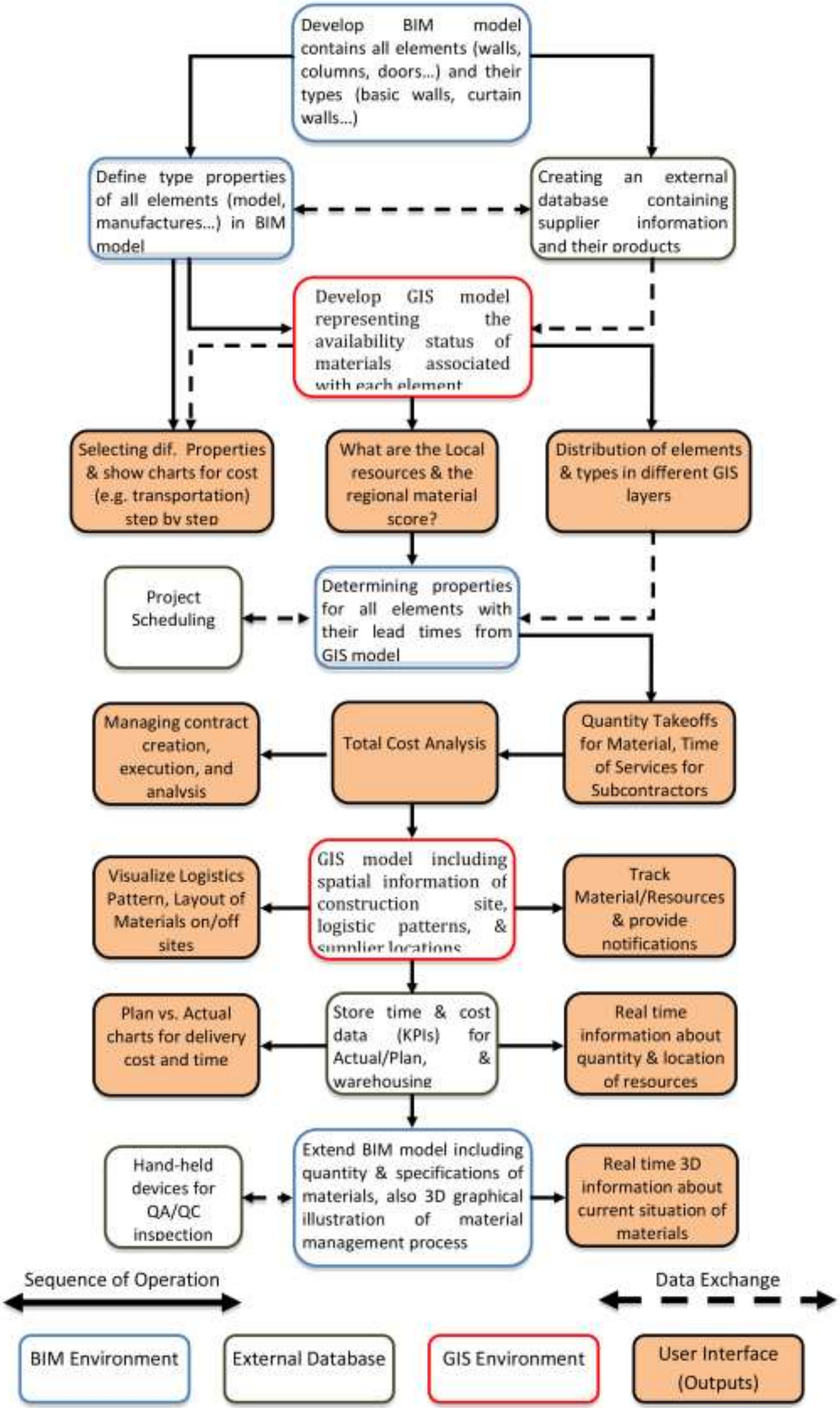
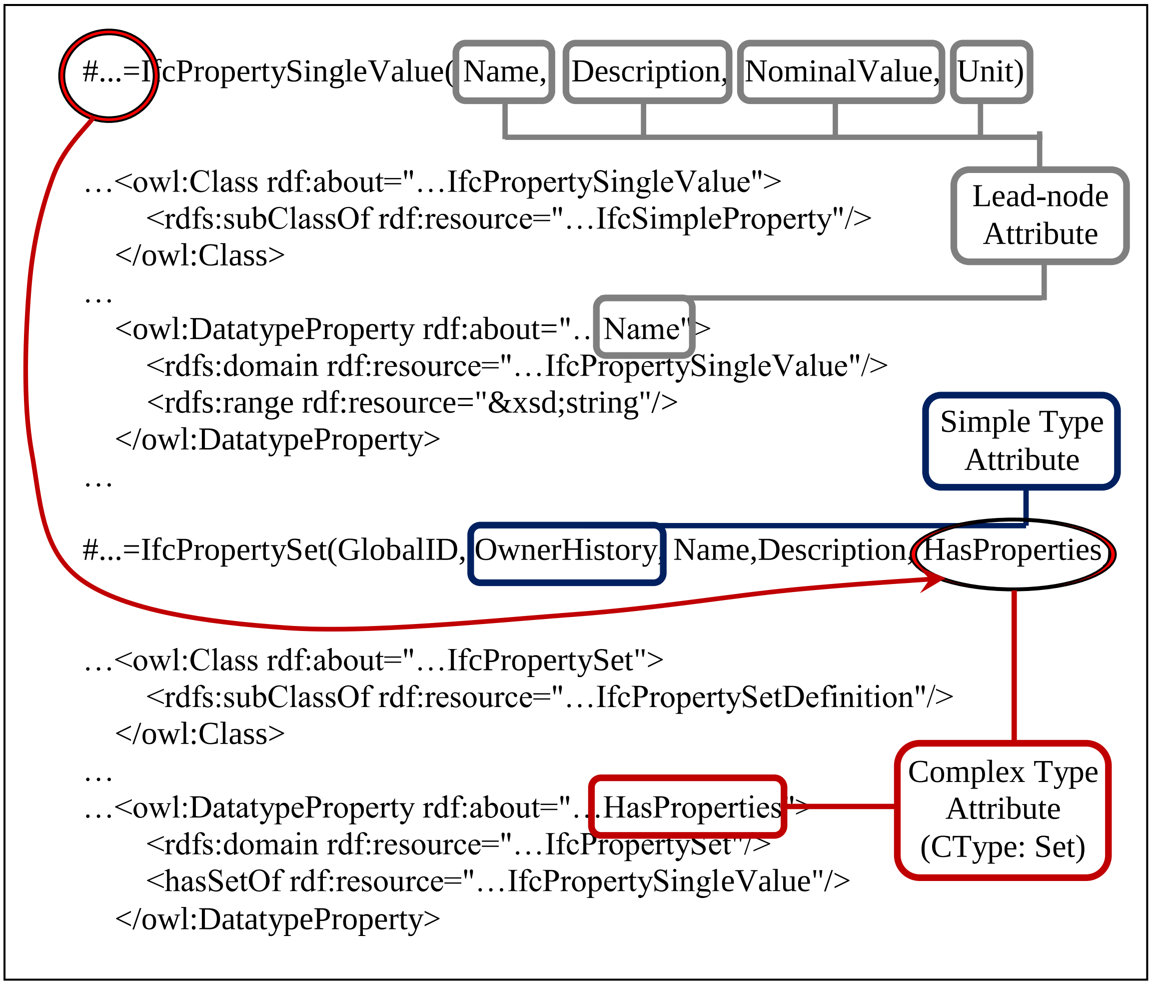


Figure 22: Information flow in the supply chain model

These relevant parameters (or new attributes) will be used to determine the status of each material. Therefore, we use “IfcPropertySingleValue” to add cost and schedule data and supplier information into the IFC in addition to the quantities (e.g. area, volume, weight) specific to each element type. The “IfcPropertySingleValue” has four attributes; Name is used to define the name of the new parameter, Description can be used to provide more information about the parameter, NominalValue is used to assign a single value, and Unit can be used to further describe the NominalValue. Once defined, we use the “IfcPropertySingleValue” as a sub-attribute for “IfcPropertySet” in order to define all extensible properties that apply to specific building products. Figure 23 shows the IFC entities and their corresponding RDF/OWL classes translated by the proposed method.



```
#...=IfcPropertySingleValue( Name, Description, NominalValue, Unit)

…<owl:Class rdf:about="…IfcPropertySingleValue">
      <rdfs:subClassOf rdf:resource="…IfcSimpleProperty"/>
   </owl:Class>
…
   <owl:DatatypeProperty rdf:about="…Name">
      <rdfs:domain rdf:resource="…IfcPropertySingleValue"/>
      <rdfs:range rdf:resource="&xsd;string"/>
   </owl:DatatypeProperty>
…

#...=IfcPropertySet(GlobalID, OwnerHistory, Name,Description, HasProperties)

…<owl:Class rdf:about="…IfcPropertySet">
      <rdfs:subClassOf rdf:resource="…IfcPropertySetDefinition"/>
   </owl:Class>
…
…<owl:DatatypeProperty rdf:about="…HasProperties">
      <rdfs:domain rdf:resource="…IfcPropertySet"/>
      <hasSetOf rdf:resource="…IfcPropertySingleValue"/>
   </owl:DatatypeProperty>
```

Figure 23: IFC entities transformation into RDF/OWL classes in the case study

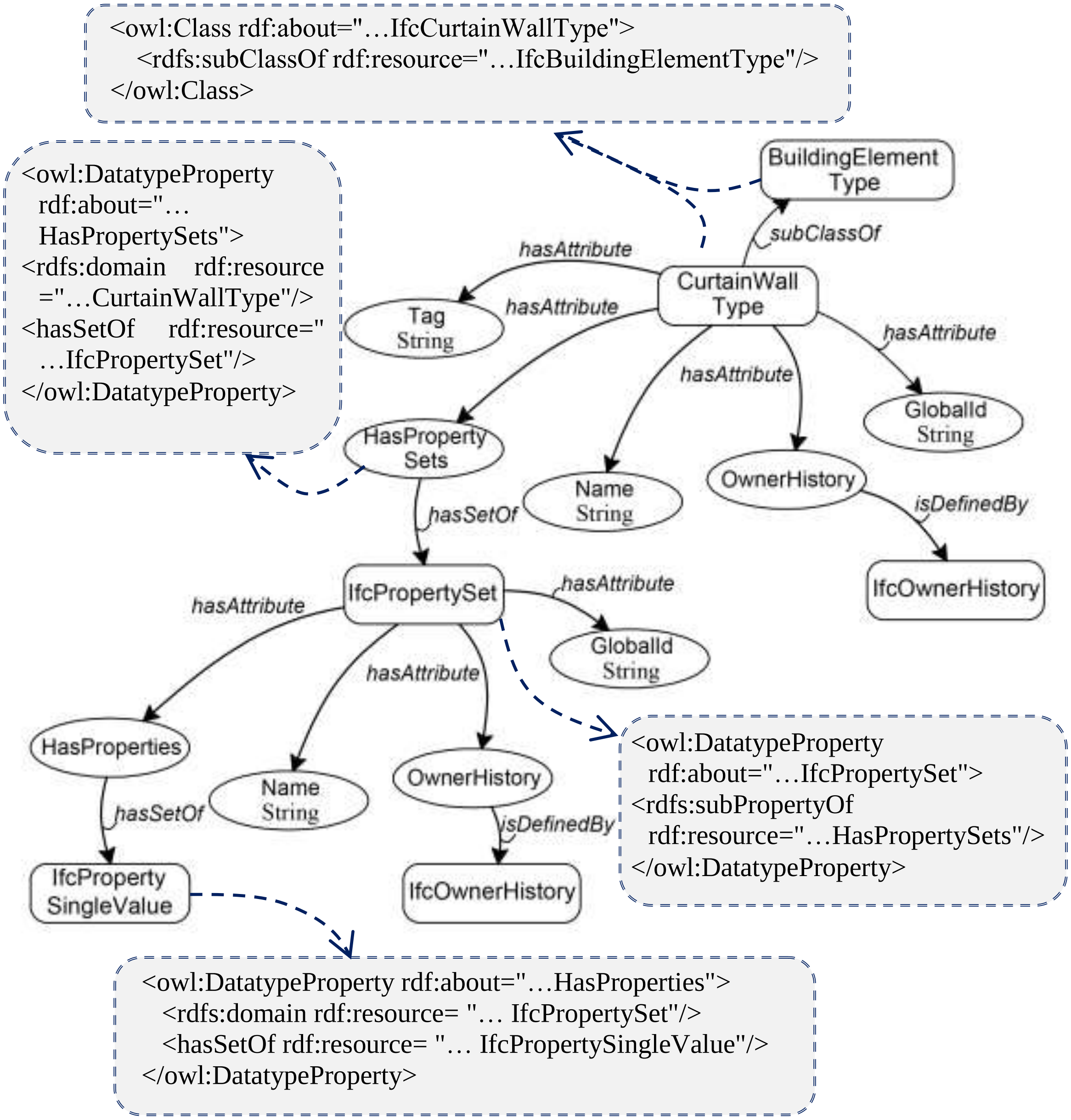
In order to enable examining the performance of the proposed method in the case study, a building material for each type of building products selected from the case study is used. The descriptive attributes of the four types of products are shown in Table 4. ETO products are specially made based on either fully designs or only details received from an engineering company (e.g., power distribution equipment, preassembled rebar components). They are defined by parameters such as manufacturer, model, raw materials, and drawings. The description of “curtain wall” is used as an example of the ETO product. Curtain wall is represented as an “IfcCurtainWall” element and implemented as a subclass of IfcBuildingElement. The “IfcCurtainWallType” is used to define the specifications of curtain wall, such as the shared properties that are common to all curtain wall types, the optional properties that are common to certain types of curtain wall, and new properties that are added to manage the supply chain. A typical “IfcCurtainWallType” entity is represented as follows (In the description below, texts in brackets [ ] refer to the attribute names and they are not presented in the IFC document):

> #[line number goes here]=IFCCURTAINWALLTYPE ([GlobalId- *as a normal and leaf-node attribute*], [OwnerHistory- *as a normal and simple type attribute*], [Name- *as an optional and leaf-node attribute*], [Description- *as an optional and leaf-node attribute*], [ApplicableOccurrence- *as an optional and leaf-node attribute*], ([HasPropertySets- *as a normal and complex type attribute*]), [RepresentationMaps- as *an optional and complex type attribute*], [Tag- *as an optional and leaf-node attribute*], [ElementType- *as an optional and leaf-node attribute*], [PredefinedType- *as a normal and leaf-node attribute*]);

Table 4: Descriptive attributes for each type of products selected from the case study

Item Type	Element Name	Grand Total	Total Area (SF)	Unit Size (ft)	Unit Weight (lb)
ETO	Curtain Wall	690	10,956	2.35 x 6.45 x 0.52	231
MTO	Metal Panel	49	477	8.31 x 1.28 x 0.08	8.2
ATO	Glass Window	211	1,849	4.64 x 1.8 x 0.56	68
MTS	Brick Veneer	88,313	20,524	0.83 x 0.28 x 0.23	0.92

Figure 24 shows the RDF graph of the "IfcCurtainWallType" entity and its corresponding RDF/OWL classes. The cost, schedule and supplier information added to the IFC model are defined by "IfcPropertySet" and attached by the "HasPropertySets" attribute. While this attribute is defined as a complex type attribute in the BIM ontology, the way it is represented in the IFC model (i.e. within parentheses) makes it possible to distinguish between the complex type and other types of attributes.



```
<owl:Class rdf:about="…IfcCurtainWallType">
   <rdfs:subClassOf rdf:resource="…IfcBuildingElementType"/>
</owl:Class>
```

```
<owl:DatatypeProperty
  rdf:about="…
  HasPropertySets">
<rdfs:domain   rdf:resource
  ="…CurtainWallType"/>
<hasSetOf    rdf:resource="
  …IfcPropertySet"/>
</owl:DatatypeProperty>
```

```
<owl:DatatypeProperty
  rdf:about="…IfcPropertySet">
<rdfs:subPropertyOf
  rdf:resource="…HasPropertySets"/>
</owl:DatatypeProperty>
```

```
<owl:DatatypeProperty rdf:about="…HasProperties">
   <rdfs:domain rdf:resource= "… IfcPropertySet"/>
   <hasSetOf rdf:resource= "… IfcPropertySingleValue"/>
</owl:DatatypeProperty>
```

Figure 24: The RDF graph and OWL Classes of IfcCurtainWallType entity

MTO products are usually products manufactured once customer orders have been placed (e.g., cast-in-place concrete, prefabricated panels). Usually, MTO products are characterized by manufacturer, model, and raw materials parameters. ATO products are also assembled (manufactured) after customer orders, however these products are usually standard or made of standard components (e.g., doors, windows). In BIM module, manufacturer and model parameters have been used for ATO products. Finally, MTS products are commodities (e.g. consumables such as bolts) characterized by short lead times. Even though manufacturer is the only parameter that used for MTS products, they should be defined as a resource for the corresponding activities in the schedule in order to address how often they are ordered and in what batch size.

Case Study Step 2 — BIM-GIS Module: develop visual model representing the availability of materials

This step involves identification of all available resources defined earlier in the BIM model and recognition of their relative distance to the construction site. Since building elements in BIM identify what needs to be purchased, it is possible to extract all information directly from the BIM tool. Once the availability of resources is developed in separate GIS layers, managers can look to the accessible materials or equipment and use only those resources that are available and meet all schedule constraints for the current project. Following the previous steps, most information like schedule of material delivery, the components of the building and their installation locations, and schedule of their relevant activities are available in GIS database. Each component is annotated with its delivery time and installation/consumption time, thus, storage duration of each component can be calculated in this step. This option is used in the BIM module of the model to calculate order due dates and demand forecasting. While demand forecast is obtained from the construction schedules, it should be borne in mind that date and duration of activities are uncertain due to the existence of various constraints.

It is noted that there are several suppliers for every item. For example, 72 different suppliers are attached to the metal panel item, including four different types according to the “metal application”; (1) preformed (prefinished) walls, (2) insulated metal panels, (3) composite metal panels, and (4) cladding panels. The locations of each supplier and the construction site are defined by “IfcPostalAddress” and are shown as a set of 2D points having x and y coordinates in GIS. The geometrical location of these address are defined by a resource from the Geonames ontology (URI: http://www.w3.org/2003/01/geo/wgs84_pos#Point). Using a coordinate system (e.g. WGS 84), each supplier is uniquely defined by its latitude and longitude coordinates as follows:

```
<owl:DatatypeProperty rdf:about="... IfcAddressLines ">
        rdfs:isDefinedBy  rdf:resource=".../geo/wgs84_pos#Point"
        <geo:latitude> latitude of the address </geo:latitude> ...
</owl:DatatypeProperty>
```

Queries such as SELECT ?supplier ?lat ?long WHERE {?x geo:point ?supplier. ?x geo:point ?point. ?point wgs84:lat ?lat. ?point wgs84:long ?long. } or Select * WHERE { ?supplier spatial:nearby (construction site location goes here 'distance goes here') ?supplier rdfs:label ?label }LIMIT 10 can facilitate the retrieval of location information of suppliers within specific distance from the construction site. We transfer the output of SPAQRL queries as a CSV file with x, y, and z-coordinate of each supplier. The geographic distribution of suppliers is analyzed by means of spatial statistical methods. In this case, GIS measures the degree to which suppliers are concentrated or dispersed around the construction site (or project location). From the GIS module, distribution of metal panel suppliers can be measured by means of geographic standard deviation.

A directional distribution of insulated metal panel's suppliers is shown in Figure 25 (ellipse shape). To compare distributions of different types of panels, new maps containing a circle centered on project location with a radius equal to the standard

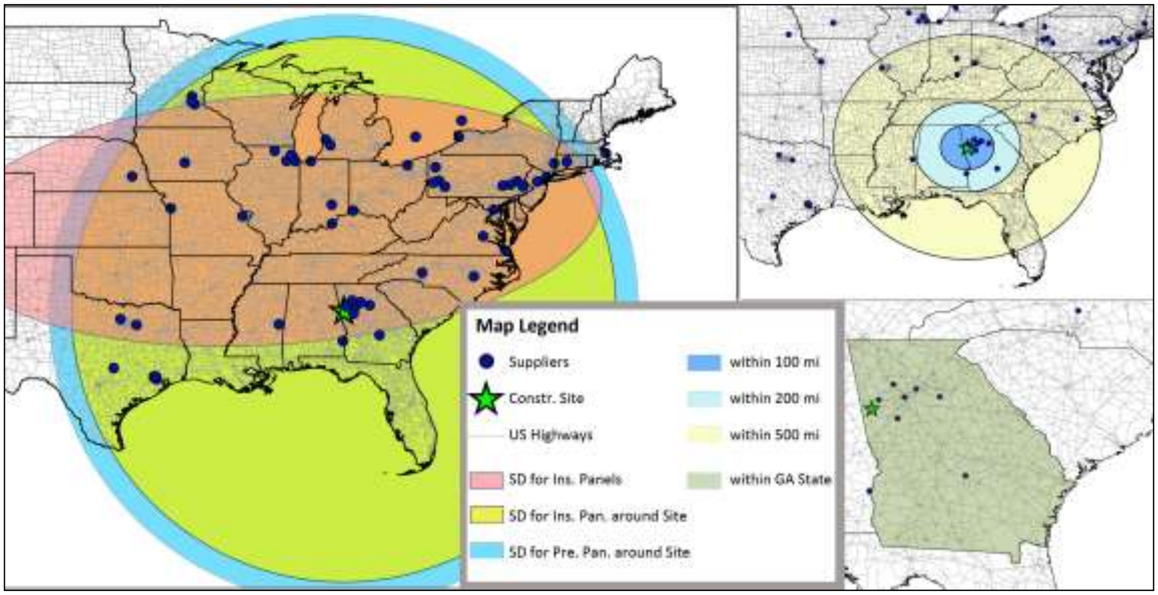


Figure 25: GIS maps representing the availability of materials in the case study

deviation of suppliers around project location are created in GIS. Figure 25 shows how dispersed are the suppliers for “preformed” (prefinished) walls and insulated metal panels with one standard deviation. In addition, information regarding the item types for each supplier is used to find suppliers of goods and services for the project. Therefore, the availability of resources that satisfies the user constraints can be developed in separate GIS layers. The most common constraint to find suppliers is to limit the distance to the construction site. Figure 25 (upper right) shows the suppliers located within 100, 200, and 500 mile of the construction site. Also, one can find the suppliers that are located within an area such as Georgia (bottom right). Because each point is annotated with its installation or consumption time, managers can look to the GIS material layers and use only those alternatives that meet all time and location constraints for the current project.

Case Study Step 3 — GIS Module: total cost analysis

In this step, GIS-based spatial analyses such as network analysis and attribute analyses have been used to provide an optimal solution to manage costs of supply chain logistics, which combines the cost of orders, warehousing and transportation. Total cost of logistics (TC) is calculated as described in the following equation:

TC = (Cost of Order) + (Inventory Cost) + (Vehicle Cost) + (Fuel Price Cost)

In the above equation, cost of order is a cost for each order placed that can be fixed or dependent on the number of units ordered. In order to minimize this component, we need to order materials together (i.e. at once). Inventory cost is the holding costs per item per unit time, that is, this component is a function of the order quantity and the period of time between delivery and installation of an item. Ordering and delivering materials as late as possible could be useful because of their low order quantity and minimal holding time. However, there will be an increase in order cost due to increased number of orders. Table 5 summarizes each of these cost elements for different types of product selected from the case study. The data for logistics costs were obtained from the contractor annual Reports, cost center reports, and financial team of the project suppliers. For example, the contractor estimated expenses for management and overhead cost of orders based on its previous records, and represents this item as the number of orders. They are specified as percentages of total material cost, to aid the comparison process. The information regarding the quantities of the selected materials for the project is also shown in Table 5.

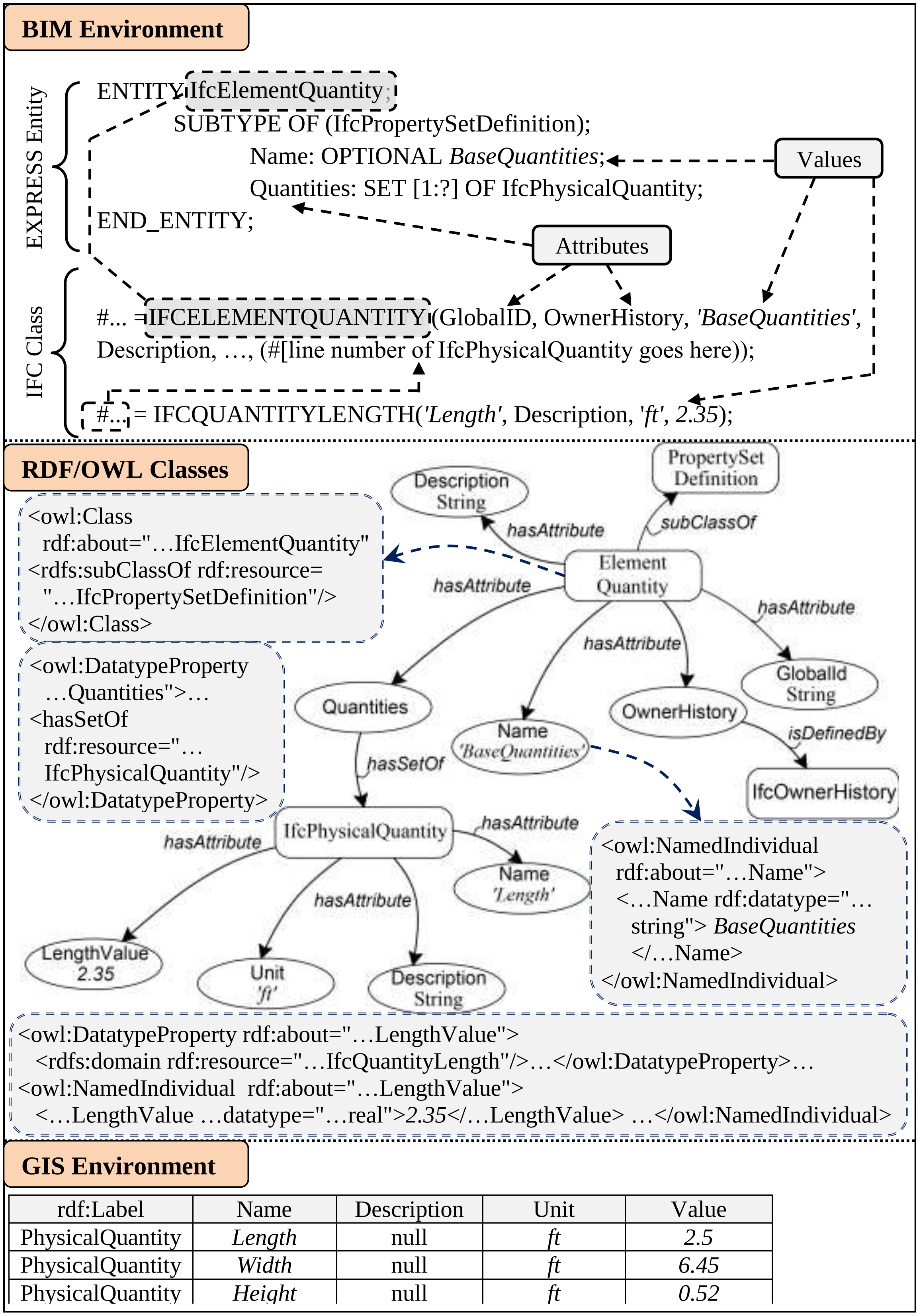
Table 5: logistics cost of products selected from the case study

Element Name	Total	Order Cost	Inventory Cost	Vehicle Cost
Curtain Wall	690	1.41xOCi	3.0E-05xQixTi	0.01x(15+2.25(2+Hr))xTr_i
Metal Panel	49	0.54xOCi	1.6E-03xQixTi	(9.3+1.4(2+Hr))xTr_i
Glass Window	211	0.91xOCi	7.6E-04xQixTi	(7.9+1.2(2+Hr))xTr_i
Brick Veneer	88,313	0.049xOCi	4.0E-07xQixTi	0.01x(40+6(2+Hr))xTr_i

OCi= Number of Orders, Qi=Quantity for the ith Order, Ti=Period of Days between Material Delivery and Installation, Hr= Travel Hours between Supplier and Construction Site, and Tri= Number of Trucks

The main requirements of GIS module are vehicles characteristics (vehicle costs, vehicle capacity, vehicles available, and vehicle travel time), average fuel price, and material properties (i.e. size and weight). Each vehicle starts from its corresponding supply point, forwards materials to a given customer (e.g. construction site) according to the demand less than the capacity of the vehicle. With regard to this need, geographic information of suppliers, quantities and properties of building components included in the BIM model are combined with network analysis in a GIS. We use either "IfcElementQuantity" or "IfcPropertySet" to define a set of quantities (e.g. length, height, gross footprint area, and etc.) of an element's physical property. Users of the proposed methodology should be aware of hierarchies of attributes and alternatives to define the values and quantities. For instance, we retrieve Area, Volume, and Length quantities for "IfcCurtainWall" from its IfcPropertySet, and Height, Length, Width, GrossFootPrintArea, and GrossVolume for "IfcWallStandardCase" from its "IfcElementQuantity".

Figure 26 shows the processes included in the first three steps of the research methodology for the Curtain Wall element, including the EXPRESS and IFC data models in a BIM environment, the resulting RDF graph and OWL Classes, and the descriptive attributes in a GIS environment. The words in italics are attribute values, and their modeling environments are shown in bold. We use "named individual" axioms to declare that a given entity is an individual. The attribute (or OWL property in the ontology) should be declared using a data type property (e.g. <owl:DatatypeProperty…-Length Value">…<IfcQuantityLength"/>…</owl:DatatypeProperty>). The CSV format for expressing the results of a SPARQL select query is useful in the case study scenario. The SPARQL CSV results format must have a header row to express the variable name. This header row will be used as the headers of each field in the attribute tables in a GIS environment. Up to this point, the supplier locations and material properties defined in the BIM model are combined together in the GIS model.



```
ENTITY IfcElementQuantity;
    SUBTYPE OF (IfcPropertySetDefinition);
        Name: OPTIONAL BaseQuantities;
        Quantities: SET [1:?] OF IfcPhysicalQuantity;
END_ENTITY;
```

```
#... =IFCELEMENTQUANTITY(GlobalID, OwnerHistory, 'BaseQuantities',
Description, …, (#[line number of IfcPhysicalQuantity goes here));
#... = IFCQUANTITYLENGTH('Length', Description, 'ft', 2.35);
```

```
<owl:Class
  rdf:about="…IfcElementQuantity"
<rdfs:subClassOf rdf:resource=
  "…IfcPropertySetDefinition"/>
</owl:Class>
```

```
<owl:DatatypeProperty
  …Quantities">…
<hasSetOf
  rdf:resource="…
  IfcPhysicalQuantity"/>
</owl:DatatypeProperty>
```

```
<owl:NamedIndividual
  rdf:about="…Name">
  <…Name rdf:datatype="…
    string"> BaseQuantities
    </…Name>
</owl:NamedIndividual>
```

```
<owl:DatatypeProperty rdf:about="…LengthValue">
  <rdfs:domain rdf:resource="…IfcQuantityLength"/>…</owl:DatatypeProperty>…
<owl:NamedIndividual  rdf:about="…LengthValue">
  <…LengthValue …datatype="…real">2.35</…LengthValue> …</owl:NamedIndividual>
```

rdf:Label	Name	Description	Unit	Value
PhysicalQuantity	*Length*	null	*ft*	*2.5*
PhysicalQuantity	*Width*	null	*ft*	*6.45*
PhysicalQuantity	*Height*	null	*ft*	*0.52*

Figure 26: Semantic transformation of material properties from BIM into GIS

Transportation cost is dependent on the type and number of trucks, the travel distance between suppliers and construction site, and the physical properties of the cargo. In order to demonstrate the model's capabilities, five different types of trucks (as listed in Table 6) are taken into account when identifying the required number of trucks. A gross vehicle weight (GVW) is the maximum weight value of a vehicle, including the total of the weights of a vehicle and cargo and a payload is defined as the total weight of all cargo that a vehicle carries. Also, the size of the loads for trucks is limited to 53×13.5×8.5 ft (L×H×W). Using the properties identified above and quantity of material for a given order, the required number of trucks can be determined. Then, fuel price cost is calculated according to the distance traveled per unit of fuel used by trucks in miles per gallon (MPG). The GIS calculates the shortest path, travel distance and travel time. For the four selected materials, the number of alternatives to be examined can be up to 203. The total cost of each material is obtained by adding transportation costs to order and inventory costs. The results of this analysis showing the optimal number of orders, time and quantity for each of them, and type and number or trucks corresponding to the least transportation cost for a given order are presented in Table 7. To make comparisons among different cost elements, units are specified as percentages of total material cost.

Table 6: Descriptive attributes for each type of trucks selected for the case study

Truck Type	GVW (lb)	Payload (lb)	Fuel Consumption (MPG)	MPG for empty truck
1	36,300	25,300	-0.0246W+6.63	6.62
2	56,000	41,050	-0.0246W+6.286	6.28
3	60,600	40,800	-0.0258W+6.285	6.26
4	80,000	55,750	-0.0255W+6.205	6.18
5	92,000	66,200	-0.0263W+5.885	5.86

W= Total Weight of Load (1000xlb)

Table 7: Total cost analysis results for the selected materials for the case study

Item Type	Distance (mile)	No. of orders	Order Details					Order Cost	Inven. Cost	Vehicle Cost	Petrol Cost
			No	Quan. (%)	Time (month)	No. of Truck	Type of Truck				
ETO	69	2	1 2	43 57	3 8	2 2	4 4	2.54	1.33	1.10	0.27
MTO	168	1	1	100	6	1	1	0.54	7.27	17.0	6.72
ATO	38	1	1	100	6	1	1	0.09	3.44	11.5	1.61
MTS	64	3	1 2 3	25 35 40	2 7 11	1 1 1	1 2 2	0.12	2.06	1.83	0.60

Figure 27 shows one example of the analysis result of the GIS for “Brick Veneer” material (as a MTS product). The model starts the process by one order and is followed by the identification of the optimal quantity and time for the order to achieve minimum logistics cost. The process is repeated for the next number of orders (i.e. 2, 3, and 4) until the total cost increases the preceding one (i.e. four orders). As can be seen, as the number of orders increases, the cost of order and inventory decreases while the transportation cost (i.e. vehicle and fuel cost) increases. Increasing the number of orders can make a substantial decrease in inventory costs due to the smaller quantities of materials in the shorter duration of storage; however, it increases the transportation costs. As shown in Figure 27, the total logistics cost is minimal (i.e. 4.61% of the total material cost) for the three orders.

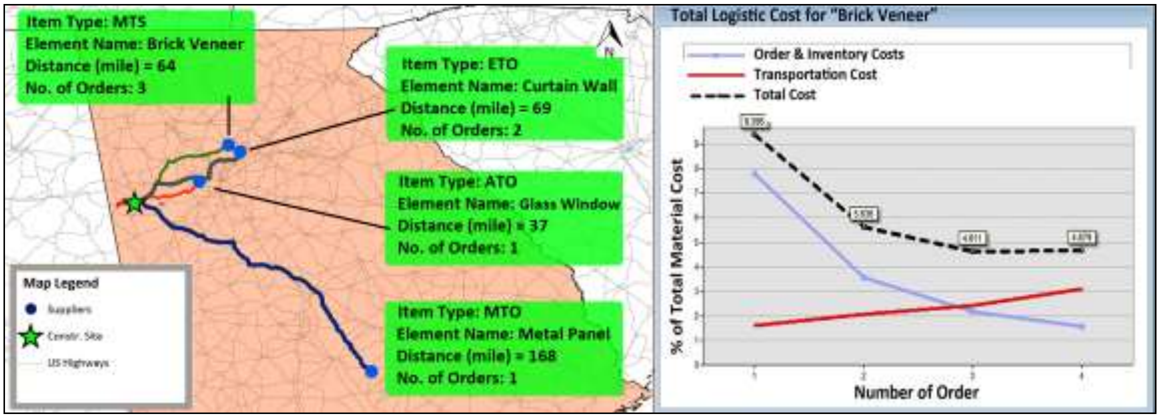


Figure 27: Total cost results based on GIS analysis for “brick veneer” in the case study

Case Study Step 4 — BIM-GIS Module: monitoring and graphical representation of material status

BIM and GIS can be applied to provide accurate and up-to-date information on the status of materials and resources. When the position of each construction resource is available, we can display the current location of a resource in a GIS map and estimate the arriving time to the predetermined construction site. Comparing the estimated times with the planned times, it is possible to provide managers with warning signals that allow them to take timely actions in response to prevent or alleviate any delays and increase delivery reliability. The status of material availability is established by tracking the building materials that are identified with corresponding ID in the BIM model and registered into the tracking system. Also, there is a link between these IDs and schedule activities, so the material needed for a given activity along with the time can be determined. When materials arrive at or their delivery date obtained from previous step, the respective material availabilities can be visualized in the BIM model.

The material status is created as instance parameters in the BIM model and assigned to all categories like walls, windows, doors, and columns. All these parameters are defined as a Date-Time variable and have two entries; one for schedule and one for actual date. Here, we take advantage of the manipulation step of the research methodology to translate SPARQL queries to semantically equivalent IFC entities. The schedule and actual date parameters are leaf node attributes, however, their corresponding IFC class might have simple or complex type attributes. The user should enter all schedule entries either manually or by using a direct link to the project schedule. On the other hand, actual entries are updated based on the element's latest status. Each element is identified and tracked using barcode assigned to the corresponding ID in the building information model. Then, we convert the query results from SPARQL into ifcXML that can be imported into a BIM model. Following this, the actual dates were compared with the schedule dates in order to alter an elements' appearance. How the visibility of objects change depends on the criteria being used to categorize elements and how many elements share the selected criteria.

Because each object in a BIM or GIS model has time attributes, it is possible to compare the actual times with the planned times to graphically show the supply chain process through different color schemes. The associated colors are blue, green, yellow, and red, for delivered, in-time (no delay), pending, and late (possible delay) respectively. The mathematical algorithm for displaying the GIS results in a meaningful way is shown in Figure 28. For this case study, there are four possible states regarding the status of "Actual Date" (AD) and "Schedule Date" (SD). ETO products have four parameters, therefore their highest value of i is four (i.e. $i \leq 4$). Using the same reasoning, only one parameter (i.e. $i \leq 1$) is considered for MTS products, which helps to know when the MTS materials are delivered to the construction site. When there are no dates among parameters, the model considers the parameter as "null". Therefore, the fifth schedule date (SD5) for ETO product is considered as "null". Furthermore, the "Pending" situation, which is coded with yellow, only occurs when there are no actual dates (AD) at all. In the absence of actual dates, the model gets the user system date as the current date and compares the current date (i.e. today) with the schedule date.

Current practice and the proposed methodology were used in parallel during this case study. Challenges in BIM and GIS data sharing and interoperability using existing approaches are twofold:

1. Data models related to building or geospatial components are specified and structured in different formats, thus, different BIM and GIS authoring tools cannot exchange and share their data models between each other.

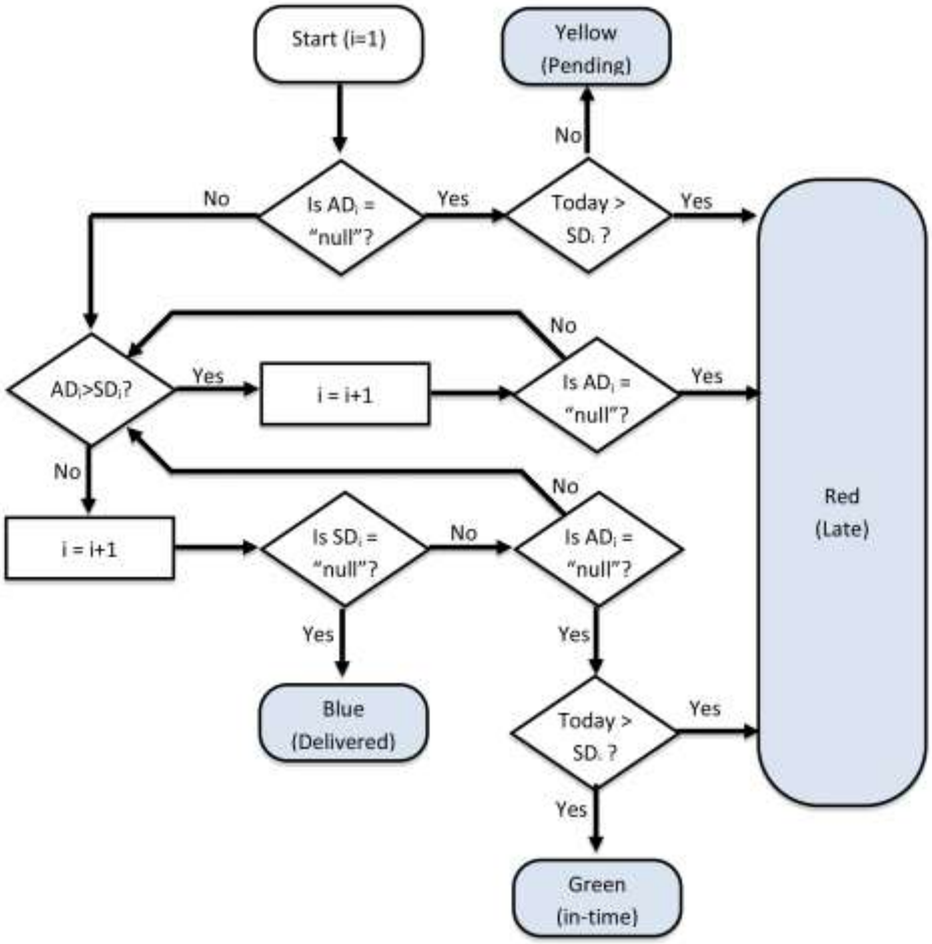


Figure 28: Status determination algorithm for color-coding (developed for the case study)

2. Even if some BIM-related information are transferred to GIS or vice versa (e.g. using a data conversion tool), there is no guarantee that another system can interpret the data being transferred.

Based on the results of the case study, we can conclude that the semantic web technology enables BIM users to represent (step 1), share (steps 2 and 3), and discover (step 4) building and GIS data through ontologies. Table 8 provides a comparison between the proposed approach and state-of-the-art tools based on the fraction of building and GIS features that can be exchanged (or supported) between BIM and GIS models without losing their semantics. These features are limited to those used for the use case examples and the case study, and divided into building elements, geometry elements and basic constructs. In order to understand what fraction of the semantics are understood (or returned) by the destination system, the recall index is categorized as “full”, “partial”, and “none”. If the semantics can be retrieved in the case of two-way exchanges (i.e. from BIM to GIS and back again), the BIM and GIS features are “fully” recalled. However, if the semantics of the features can be delivered only in one-way exchange, they are “partially” recalled. We have “no” recall when the semantics cannot be shared and reused across BIM and GIS applications. Almost two third of the features listed in Table 8 cannot be semantically shared by state-of-the-art tools, and only 24 percent (15 out of 62) can be partially transferred between BIM and GIS tools. In contrast, the proposed approach partially recalls around 42 percent (26 out of 62) of the BIM and GIS semantics. Moreover, the full recall rate using the proposed approach is considerably higher than that for the existing tools. According to the results of the evaluation step, around 40 percent of the semantics are retrieved using the proposed approach in the case of two-way exchanges, while only around 10 percent can be conveyed using the state-of-the-art tools. These results provide evidence for the effectiveness of our approach for extending the interoperability between the building modeling and geospatial analysis tools, which will enhance the efficiency and effectiveness of automated data acquisition and information sharing among project stakeholders.

Table 8: Recall results for different BIM and GIS features used in the study

BIM and GIS Features	**State-of-the-art tools**			**Proposed Approach**		
	Full	**Partial**	**None**	**Full**	**Partial**	**None**
Building Elements						
Antenna			✓		✓	
Beam			✓		✓	
Boiler			✓		✓	
Bridge			✓			✓
Building structure			✓	✓		

Building storey			✓	✓		
Chiller			✓			✓
Column			✓		✓	
Curtain wall			✓		✓	
Construction equipment		✓			✓	
Door			✓		✓	
Fence		✓		✓		
Foundation			✓		✓	
Furniture			✓			✓
Gate			✓		✓	
Helipad			✓		✓	
Levee		✓		✓		
Light			✓	✓		
Material presentation			✓			✓
Material type			✓		✓	
Parking area	✓			✓		
Rail (inside the building)			✓			✓
Railway			✓		✓	
Roof		✓			✓	
Sign			✓			✓
Slab			✓	✓		
Structural pile			✓		✓	
Window			✓		✓	
Geometry Elements						
Analytic surface		✓		✓		
Bounding edges			✓		✓	
Bounding loops			✓		✓	
Direction vector			✓	✓		
Elevation			✓	✓		
Extruded area		✓			✓	

Geometric surface		✓		✓		
Grid		✓			✓	
Line	✓			✓		
Location in 3D space			✓		✓	
Orientation in 3D space			✓		✓	
Point	✓			✓		
Rectangular coordinate system	✓			✓		
Road junction (intersection)			✓		✓	
Survey point		✓		✓		
Topological representation		✓		✓		
Volume			✓	✓		
Basic Constructs						
Address			✓		✓	
Asset			✓			✓
Basic electrical characteristics			✓			✓
Calendar date			✓		✓	
Capacity			✓			✓
Cost		✓			✓	
Data Provider Role		✓			✓	
Dimensions of the base quantities			✓	✓		
Geometric representation style		✓				✓
Globally Unique Identifier		✓		✓		
Layer style (color, line style, etc.)		✓				✓
Ownership			✓	✓		
Process control (e.g. constraints)	✓			✓		
Text	✓			✓		
Units of the base quantities			✓	✓		
Vegetation			✓	✓		
Water surface			✓			✓

Limitations of System

Since semantic web technologies are still developing and maturing, it is often time consuming to find efficient ways of using these technologies. As can be seen from this study, there are very few globally-agreed ontologies available for the construction domain. Hence, multi-disciplinary professionals involved in AEC projects develop their own ontologies without respect to other ontologies, thus limiting the effective transfer of information among project team members. Ontologies are also evolving as part of the integrated system and new concepts and features are added to the AEC and geospatial domains of knowledge. Because the proposed methodology adopted ontology mapping techniques, it has the ability to overcome the short-term deployment obstacles. However, the long-term effectiveness is dependent upon developing a data framework that automatically integrates itself with the globally-agreed ontologies.

The amount of information providing from different sources has increased gradually with the increasing complexity of modern construction projects and the number of multi-disciplinary teams involved in a construction project. Semantics of each source of information are currently developed independently, thus, two ontologies might have different levels of granularity. For example, there is no equivalent concept for “surface water” in the BIM ontology, however, the concept can be defined and modelled in a GIS environment. The “vegetation” concept is defined as a general class in the BIM ontology, but it can further be divided into plants or cultivated grass in the GIS ontology. When there is no equivalent of a concept in the destination system, the proposed approach cannot fully capture the semantics of the concept. A potential solution is to consider a most similar entity class across the destination ontology, however, this approach is not applied in the proposed approach.

GML is used in the proposed methodology to express geographic information in a manner that can be readily encoded and shared. However, GML is a text-based document format which makes it incredibly inefficient for network, processor and storage performances. Because an RDF file contains a bunch of information about all of the entries of each resource, converting building or GIS data to RDF tends to produce too large outputs. Keeping this very large number of triples in one big file may not be the best option to query and retrieve the data, because it reads the entire dataset for each query. One way is to use a database manager optimized for RDF triples, however, this concept is not applied in this study as the aim of the study is to investigate the feasibility of applying semantic web technology to enable semantic interoperability between BIM and GIS. The same problem applied to ifcXML files, because they are very long and complex files even for very simple query results. The SPARQL result used in this paper consisted of only eight variables, yet the ifcXML file was almost 3,000 lines of code.

CHAPTER VI -

CONCLUSION and FUTURE WORK

The primary objective of this study was to extend the semantic interoperability between the AEC (BIM in particular) and the geospatial domains. The contributions of the proposed model to the existing body of knowledge are threefold, as shown schematically in Figures 29 and 30. The first is to enhance data exchange and integration between BIM and GIS from syntactic level to semantic level by providing semantics of the data. We model different terrain elements (e.g. bare ground, body of water, vegetation) and man-made structures (e.g. temporary facilities, their locations and properties) as a set of concepts within geospatial domain knowledge, however, their precise meaning cannot be understood by BIM users who are not familiar with geospatial domain knowledge.

The geospatial ontology is semantically richer than the AEC otology in terms of the topographic features, thus, we cannot retrieve most of the concepts defined in a GIS model due to missing semantic information attached with GIS models. In the current practice, the bare ground concept should be represented as a set of data points and then re-created in the BIM environment. The facility location should be represented as 2D CAD data and then annotated with appropriate keywords. The BIM user can search the data just by those keywords and retrieve the geometry as a 2D drawing. The use case examples described in this chapters show how the research methodology enables us to transfer topographic features and relationships between these features to BIM.

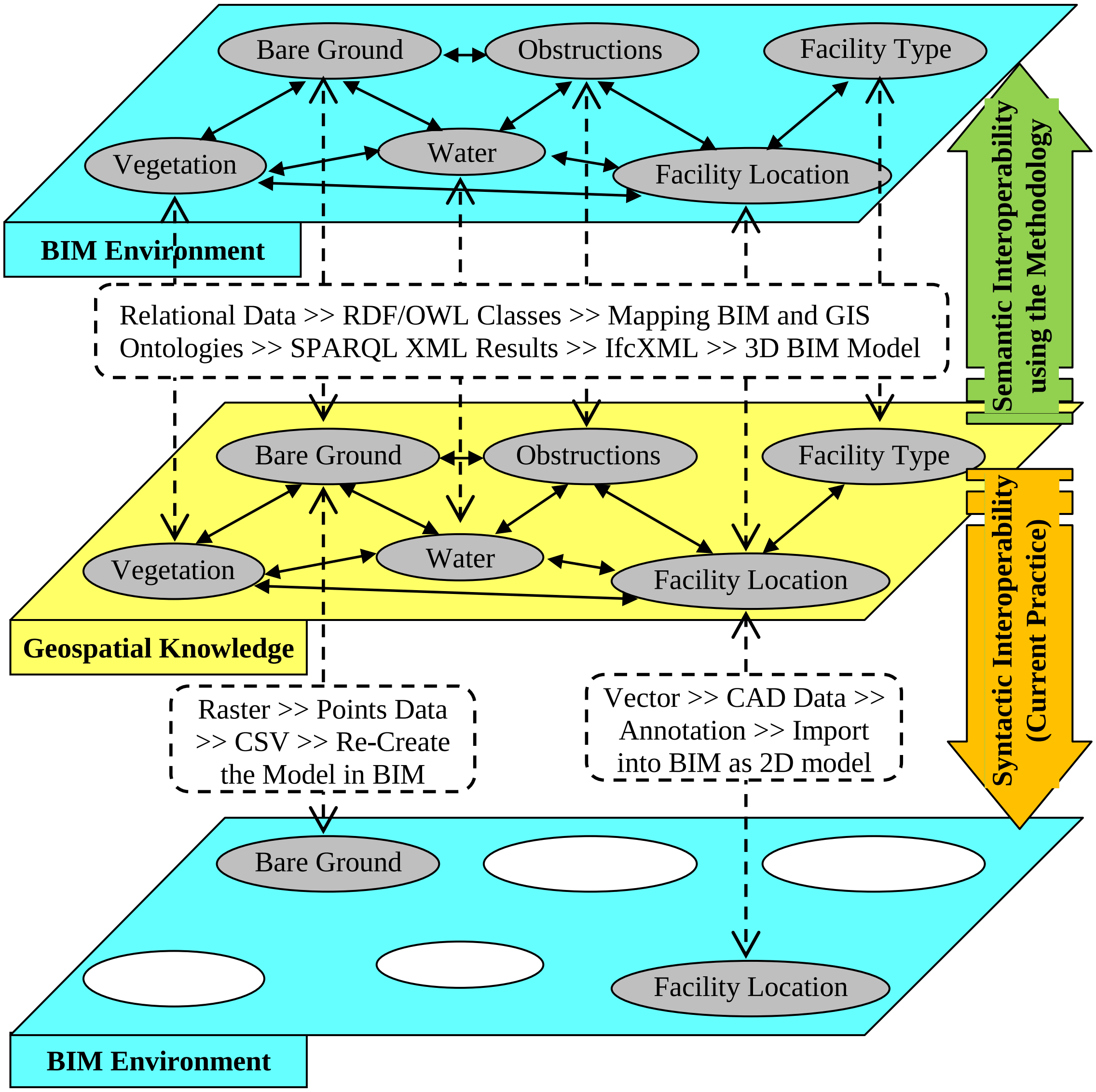


Figure 29: Comparison between the semantic (proposed method) and syntactic (current practice) interoperability of GIS data exchanged in the use case examples and case study

Second, the proposed method allows BIM users to query and retrieve building data publishing from different sources. We developed a process for query and access to ontology-based web services that converts query results from SPARQL into ifcXML in response to the need to access multiple heterogeneous data sources. The process developed in this study considers the structure and context information as well as the semantics of both the source and target elements to translate query results into the ifcXML file.

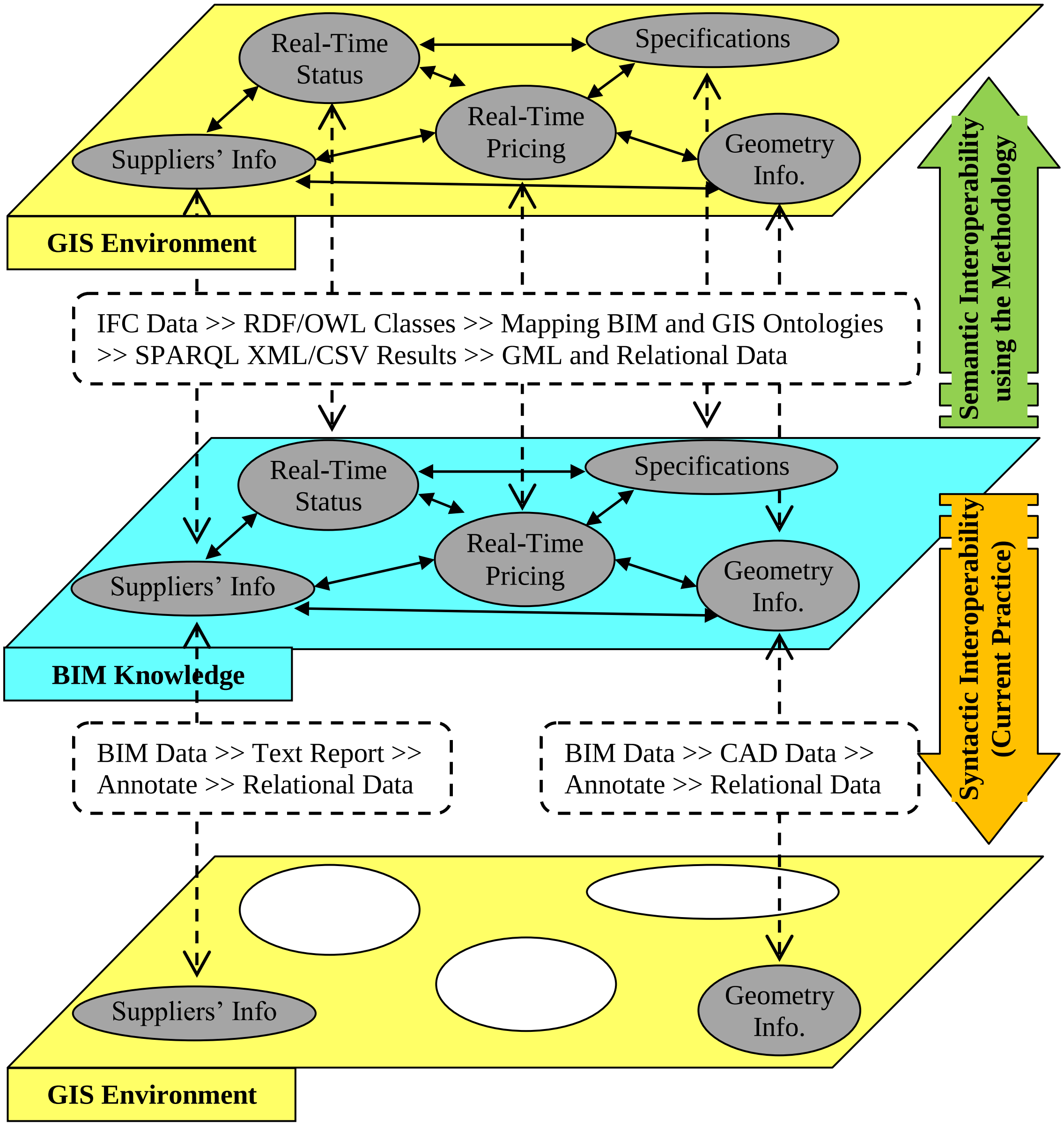


Figure 30: Comparison between the semantic (proposed method) and syntactic (current practice) interoperability of BIM data exchanged in the use case examples and case study

Third, we constructed a new ontology based on the EXPRESS schema at the application level. This BIM ontology provides a way for seamless integration of building and construction related data that encompasses all IFC classes with different attributes. The inconsistent level of details between BIM and GIS ontologies can hinder the quality of data and information sharing. Therefore, most of the IFC building's elements cannot be semantically transferred into the GIS model. In the current practice, the BIM user can transfer the geometry and descriptive information that can be exported either as CAD files or text reports. However, they should be annotated with appropriate keywords and then manually imported into the GIS model. In contrast, the proposed method enables the user to query the content of the data sources.

The case study results of the proposed methodology demonstrate that semantic web technology can be a way to enable semantic interoperability between building and geospatial heterogeneous data. While the results are encouraging for the use case examples and the case study, additional case studies would be necessary to examine the applicability of semantic web technology to the AEC domain. The fraction of building and GIS features that can be exchanged by the proposed approach in comparison with the state-of-the-art tools (Table 8) recognizes the semantic web as a key-enabler for integration of data in the construction process. It is expected that the proposed approach would enable process integration that can lead to improvements in the flow of BIM and GIS information. How semantic web technology enables both data and process integration is not addressed in the use case examples. Therefore, it is recommended to apply the proposed approach for different use cases that focus on the interaction between the BIM user and the system (process integration). One of the best use cases for semantic web technology is probably large-scale BIM and GIS data integration across institutional and national boundaries (e.g. emergency response and disaster management).

The methodology demonstrates how to represent IFC contents as RDF triples, so one of the future improvements of this work is to develop tools for automatic generation of semantic data models based on IFC-models. This thesis provided a conceptual requirement for the automatic reconstruction of building information models from uninterrupted 3D Models. The IFC to RDF/OWL converter can be written in php scripting language, as it is a server-side programming language designed for web development. It should be able to receive the IFC file from a BIM server, extract the needed information with respect to the structure of RDF format, and store it in a temporal database. The same approach can be utilized for converting XML results into ifcXML. This interface should allow users to query and access building and geospatial data at any time over the web from data providers.

Linked data, as a concept that arises within the paradigm of semantic web, helps to overcome interoperability challenges to enhance information exchange in the AEC domain. There are four principles to publish our BIM and GIS data as linked data (Berners-Lee 2006): (1) use URIs as names for things, (2) use the standards (e.g. RDF, SPARQL) to declare a list of terms and their relationships, (3) use HTTP URIs to describe the resource that the URI identifies, and (4) include links to other URIs so various RDF vocabularies have a specific relationship to another resource on the web. This thesis focuses only on the first two principles to publish data in a form that machines can naturally understand. Future work can extend this methodology to consider all principles of linked data.

REFERENCES

Adachi, Y. (2003). "Overview of partial model query language." *Proceedings of the 10th ISPE International Conference on Concurrent Engineering*Madeira, Portugal, 549-555.

Agdas, D., and Ellis, R. D. (2010). "The potential of XML technology as an answer to the data interchange problems of the construction industry." *Construction Management and Economics*, 28(7), 737-746.

Akinci, B., Karimi, H., Pradhan, A., Wu, C.-C., and Fichtl, G. (2010). "CAD and GIS interoperability through semantic web services." *CAD and GIS Integration*, 199.

Alder, M. A. (2006). "Comparing time and accuracy of building information modeling to on-screen takeoff for a quantity takeoff of a conceptual estimate." Master of Science, Brigham Young University, UK.

Anumba, C., Pan, J., Issa, R., and Mutis, I. (2008). "Collaborative project information management in a semantic web environment." *Engineering, Construction and Architectural Management*, 15(1), 78-94.

Anumba, C. J., Issa, R. R., Pan, J., and Mutis, I. (2008). "Ontology-based information and knowledge management in construction." *Construction Innovation: Information, Process, Management*, 8(3), 218-239.

ARQ (2011). "ARQ - A SPARQL Processor for Jena." <http://jena.apache.org/documentation/query/>. (December, 20, 2013).

Azhar, S., Carlton, W. A., Olsen, D., and Ahmad, I. (2011). "Building information modeling for sustainable design and LEED rating analysis." *Automation in construction*, 20(2), 217-224.

Bakis, N., Aouad, G., and Kagioglou, M. (2007). "Towards distributed product data sharing environments—Progress so far and future challenges." *Automation in Construction*, 16(5), 586-595.

Balachandar, K., Thirumagal, E., Aishwarya, D., and Rajkumar, R. (2013). "Ontology Mapping Techniques and Approaches." *International Journal of Computer Applications*, 65(24).

Bansal, V. K. (2011). "Use of GIS and Topology in the Identification and Resolution of Space Conflicts." *Journal of Computing in Civil Engineering*, 25(2), 159-171.

Bansal, V. K., and Pal, M. (2007). "Potential of geographic information systems in building cost estimation and visualization." *Automation in Construction*, 16(3), 311-322.

Bansal, V. K., and Pal, M. (2009). "Construction schedule review in GIS with a navigable 3D animation of project activities." *International Journal of Project Management*, 27(5), 532-542.

Bansal, V. K., and Pal, M. (2009). "Extended GIS for construction engineering by adding direct sunlight visualisations on buildings." *Construction Innovation: Information, Process, Management*, 9(4), 406-419.

Beetz, J. (2009). "Facilitating distributed collaboration in the AEC/FM sector using Semantic Web Technologies." Eindhoven University of Technology.

Berners-Lee, T. (2006). "Linked data." <http://www.w3.org/DesignIssues/LinkedData.html>. (December 20, 2013).

Bishr, Y. (1998). "Overcoming the semantic and other barriers to GIS interoperability." *International Journal of Geographical Information Science*, 12(4), 299-314.

Borrmann, A., Van Treeck, C., and Rank, E. (2006). "Towards a 3D spatial query language for building information models." *Proceedings of the International Conference of Computing and Decision Making in Civil and Building Engineering (ICCCBE-XI)*Montreal, Canada, 1374-1385.

Brunnermeier, S. B., and Martin, S. A. (2002). "Interoperability costs in the US automotive supply chain." *Supply Chain Management: An International Journal*, 7(2), 71-82.

Cheng, M. Y., and Yang, S. C. (2001). "GIS-based cost estimates integrating with material layout planning." *Journal of Construction Engineering and Management*, 127, 291-299.

Cheung, F. K., Rihan, J., Tah, J., Duce, D., and Kurul, E. (2012). "Early stage multi-level cost estimation for schematic BIM models." *Automation in Construction*, 27, 67-77.

Choi, J. W., Kim, S. A., Lertlakkhanakul, J., and Yeom, J. H. (2008) "Developing Ubiquitous Space Information Model for Indoor GIS Service in Ubicomp Environment." *Proc., 4th Int. Conference on Networking Computing and Advanced Information Management,* IEEE, 381-388.

Cromley, E. K., and McLafferty, S. (2012). *GIS and public health*, Guilford Press.

Crowther, P., and Hartnett, J. (2001) "Handling Spatial Objects in a GIS Database-Relational v Object Oriented Approaches." *Proc., CD Proceedings of the 6th International Conference on GeoComputation, University of Queensland, Brisbane, Australia*, Citeseer, 24-26.

Curry, E., O'Donnell, J., Corry, E., Hasan, S., Keane, M., and O'Riain, S. (2013). "Linking building data in the cloud: Integrating cross-domain building data using linked data." *Advanced Engineering Informatics*, 27(2), 206-219.

Cutting-Decelle, A. F., Das, B., Young, R., Case, K., Rahimifard, S., Anumba, C. J., and Bouchlaghem, N. (2007). "A review of approaches to supply chain communications: from manufacturing to construction." *Journal of Information Technology in Construction (ITcon)*, 12, 73-102.

Davies, J., Fensel, D., and Harmelen, F. V. (2003). *Towards the Semantic Web: Ontology-driven Knowledge Management*, John Wiley & Sons, Chichester, UK.

Deutsch, R. (2011). *BIM and Integrated Design: Strategies for Architectural Practice*, John Wiley & sons.

Döllner, J., and Hagedorn, B. (2007). "Integrating urban GIS, CAD, and BIM data by servicebased virtual 3D city models." *Urban and Regional Data Management-UDMS Annual 2007*Stuttgart, Germany, 157-160.

Eastman, C., Jeong, Y.-S., Sacks, R., and Kaner, I. (2009). "Exchange model and exchange object concepts for implementation of national BIM standards." *Journal of Computing in Civil Engineering*, 24(1), 25-34.

Eastman, C., Teicholz, P., Sacks, R., and Liston, K. (2011). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*, John Wiley & Sons.

El-Diraby, T., Lima, C., and 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.

El-Diraby, T., and Osman, H. (2011). "A domain ontology for construction concepts in urban infrastructure products." *Automation in Construction*, 20(8), 1120-1132.

El-Gohary, N. M., and El-Diraby, T. E. (2009). "Merging architectural, engineering, and construction ontologies." *Journal of Computing in Civil Engineering*, 25(2), 109-128.

El-Gohary, N. M., and El-Diraby, T. E. (2010). "Domain ontology for processes in infrastructure and construction." *Journal of Construction Engineering and Management*, 136(7), 730-744.

Elbeltagi, E., and Dawood, M. (2011). "Integrated visualized time control system for repetitive construction projects." *Automation in Construction*, 20(7), 940-953.

Elghamrawy, T., Boukamp, F., and Kim, H.-S. (2009). "Ontology-Based, Semi-Automatic Framework for Storing and Retrieving On-Site Construction Problem Information-An RFID-Based Case Study." *Construction Research Congress* ASCE, Seattle, Washington, 457-466.

Ergen, E., Akinci, B., and Sacks, R. (2007). "Tracking and locating components in a precast storage yard utilizing radio frequency identification technology and GPS." *Automation in Construction*, 16(3), 354-367.

Eskrootchi, R., Karan, E. P., and Sebt, M. H. (2008). "Optimal Location of Concrete Batch Plant by GIS." *Proc., CSCE 2008 Annual Conference*, 241-250.

Fidan, G., Dikmen, I., Tanyer, A. M., and Birgonul, M. T. (2011). "Ontology for relating risk and vulnerability to cost overrun in international projects." *Journal of Computing in Civil Engineering*, 25(4), 302-315.

Fu, C., Kaya, S., and Aouad, M. K. G. (2007). "The development of an IFC-based lifecycle costing prototype tool for building construction and maintenance: integrating lifecycle costing to nD modelling." *Construction Innovation: Information, Process, Management*, 7(1), 85-98.

Fuertes, A., Forcada, N., Casals, M., Gangolells, M., and Roca, X. (2007). "Development of an Ontology for the Document Management Systems for Construction." *Complex Systems Concurrent Engineering*, Springer, 529-536.

GCR, N. (2004). *Cost analysis of inadequate interoperability in the US capital facilities industry*, National Institute of Standards and Technology.

GeoTools (2013). "GeoTools." <http://www.geotools.org/>. (August 30, 2013).

GIS, Q. (2013). "Quantum GIS." <http://www.qgis.org/>. (August 30, 2013).

Goedert, J. D., and Meadati, P. (2008). "Integrating construction process documentation into building information modeling." *Journal of Construction Engineering and Management*, 134(7), 509-516.

Goodchild, M., Egenhofer, M., Fegeas, R., and Kottman, C. (1999). *Interoperating geographic information systems*, Kluwer Academic Publishers, Norwell, Massachusetts.

Hayes, J., and Gutierrez, C. (2004). "Bipartite graphs as intermediate model for RDF." *Proceedings of the 3rd International Semantic Web Conference, LNCS*, Springer, 47-61.

Hijazi, I., Ehlers, M., Zlatanova, S., Becker, T., and van Berlo, L. (2011). "Initial investigations for modeling interior Utilities within 3D Geo Context:

Transforming IFC-interior utility to CityGML/UtilityNetworkADE." *Advances in 3D Geo-information sciences*, Springer, 95-113.

Horrocks, I., Patel-Schneider, P. F., and Van Harmelen, F. (2003). "From SHIQ and RDF to OWL: The making of a web ontology language." *Web semantics: science, services and agents on the World Wide Web,* 1(1), 7-26.

Hu, W., Jian, N., Qu, Y., and Wang, Y. (2005). "GMO: A graph matching for ontologies." *Proceedings of K-CAP Workshop on Integrating Ontologies*Banff, Canada, 41-48.

Irizarry, J., and Karan, E. P. (2012). "Optimizing location of tower cranes on construction sites through GIS and BIM integration." *Journal of Information Technology in Construction (itcon),* 17, 351-366.

Irizarry, J., Karan, E. P., and Jalaei, F. (2013). "Integrating BIM and GIS to improve the visual monitoring of construction supply chain management." *Automation in Construction*, 31, 241-254.

Isikdag, U., Underwood, J., and Aouad, G. (2008). "An investigation into the applicability of building information models in geospatial environment in support of site selection and fire response management processes." *Advanced Engineering Informatics*, 22(4), 504-519.

Jiang, S., Zhang, J., and Zhang, H. (2013). "Ontology-based Semantic Retrieval for Risk Management of Construction Project." *Journal of Networks*, 8(5).

Kalfoglou, Y. (2009). *Cases on semantic interoperability for information systems integration: practices and applications*, Information Science Reference, Hershey, Pennsylvania.

Karan, E., and Ardeshir, A. (2008). "Safety Assessment of Construction Site Layout Using Geographic Information System." *AEI 2008*, 1-14.

Karan, E., Sivakumar, R., Irizarry, J., and Guhathakurta, S. (2014). "Digital Modeling of Construction Site Terrain using Remotely Sensed Data and Geographic Information Systems Analyses." *Journal of Construction Engineering and Management*, 140(3), 04013067.

Karan, E. P., and Irizarry, J. (2014). "Developing a Spatial Data Framework for Facility Management Supply Chains." *Construction Research Congress 2014*, D. Castro-Lacouture, J. Irizarry, and B. Ashuri, eds., American Society of Civil Engineers, Atlanta, GA, 2355-2364.

Karimi, H. A., and Akinci, B. (2009). *CAD and GIS integration*, Auerbach Publications, Boca Raton, Florida.

Kim, H., and Grobler, F. (2007). "Building ontology to support reasoning in early design." *Computing in Civil Engineering*, L. S. a. B. Akinci, ed.Pittsburgh, PA, 151-158.

Laat, R., and Berlo, L. (2011). "Integration of BIM and GIS: The Development of the CityGML GeoBIM Extension." *Advances in 3D Geo-Information Sciences*, T. H. K. Kolbe, G.; Nagel, C., ed.Berlin, Germany, 211-225.

Lapierre, A., and Cote, P. (2007). "Using Open Web Services for urban data management: A testbed resulting from an OGC initiative for offering standard CAD/GIS/BIM services." *Proc., Urban and Regional Data Management. Annual Symposium of the Urban Data Management Society*, 381-393.

Lee, S.-K., Kim, K.-R., and Yu, J.-H. (2013). "BIM and ontology-based approach for building cost estimation." *Automation in Construction*, 41, 96-105.

Leite, F., Akcamete, A., Akinci, B., Atasoy, G., and Kiziltas, S. (2011). "Analysis of modeling effort and impact of different levels of detail in building information models." *Automation in Construction*, 20(5), 601-609.

Li, H., Kong, C. W., Pang, Y. C., Shi, W. Z., and Yu, L. (2003). "Internet-Based Geographical Information Systems System for E-Commerce Application in Construction Material Procurement." *Journal of Construction Engineering and Management*, 129(6), 689-697.

Lima, C., Diraby, T., Fies, B., Zarli, A., and Ferneley, E. (2003). "The E-Cognos Project: Current Status and Future Directions of an Ontology-Enabled IT Solution Infrastructure Supporting Knowledge Management in Construction." *Construction Research Congress*, 1-8.

Lima, C., El-Diraby, T., and Stephens, J. (2005). "Ontology-based optimization of knowledge management in e-construction." *Journal of IT in Construction*, 10, 305-327.

Liu, R., and Issa, R. (2012). "3D Visualization of Sub-surface Pipelines in Connection with the Building Utilities: Integrating GIS and BIM for Facility Management." *Proc., Computing in Civil Engineering (2012)*, ASCE, 341-348.

Ma, Z., Shen, Q., and Zhang, J. (2005). "Application of 4D for dynamic site layout and management of construction projects." *Automation in Construction*, 14(3), 369-381.

Mazairac, W., and Beetz, J. (2013). "BIMQL–An open query language for building information models." *Advanced Engineering Informatics*, 27(4), 444-456.

Mitchell, J., and Hans Schevers, C. (2007). "Adopting BIM for facilities management: Solutions for managing the Sydney Opera House." *Cooperative Research Center for Construction Innovation, Brisbane, Australia*.

Nagel, C., Stadler, A., and Kolbe, T. H. (2009). "Conceptual requirements for the automatic reconstruction of building information models from uninterpreted 3D models." *Proceedings of the International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*Vancouver, Canada, 46-53.

Nepal, M. P., Staub-French, S., Pottinger, R., and Webster, A. (2012). "Querying a building information model for construction-specific spatial information." *Advanced Engineering Informatics*.

Niknam, M., and Karshenas, S. (2013). "A Semantic Web Service Approach to Construction Cost Estimating." *ASCE International Workshop on Computing in Civil Engineering*Los Angeles, CA.

OGC (2007). "OGC Web Services Architecture for CAD GIS and BIM.", < https://portal.opengeospatial.org/files/?artifact_id=28802.>. (December 20, 2013).

OGC (2008). "Open Geospatial Consortium. OpenGIS® City Geography Markup Language (CityGML) Encoding Standard. ." < https://portal.opengeospatial.org /files/?artifact_id=28802. >. (December 20, 2013).

Pandit, A., and Zhu, Y. (2007). "An ontology-based approach to support decision-making for the design of ETO (Engineer-To-Order) products." *Automation in Construction*, 16(6), 759-770.

Park, C.-S., Lee, D.-Y., Kwon, O.-S., and Wang, X. (2013). "A framework for proactive construction defect management using BIM, augmented reality and ontology-based data collection template." *Automation in Construction*, 33, 61-71.

Pauwels, P., Van Deursen, D., Verstraeten, R., De Roo, J., De Meyer, R., Van de Walle, R., and Van Campenhout, J. (2011). "A semantic rule checking environment for building performance checking." *Automation in Construction*, 20(5), 506-518.

Peachavanish, R., Karimi, H. A., Akinci, B., and Boukamp, F. (2006). "An ontological engineering approach for integrating CAD and GIS in support of infrastructure management." *Advanced Engineering Informatics*, 20(1), 71-88.

Peña-Mora, F., Chen, A. Y., Aziz, Z., Soibelman, L., Liu, L. Y., El-Rayes, K., Arboleda, C. A., Lantz Jr, T. S., Plans, A. P., and Lakhera, S. (2010). "Mobile Ad Hoc Network-Enabled Collaboration Framework Supporting Civil Engineering Emergency Response Operations." *Journal of Computing in Civil Engineering*, 24(3), 302-312.

Schlueter, A., and Thesseling, F. (2009). "Building information model based energy/exergy performance assessment in early design stages." *Automation in Construction*, 18(2), 153-163.

Schraw, G. (1998). "Promoting general metacognitive awareness." *Instructional science*, 26(1-2), 113-125.

Sebt, M. H., Karan, E. P., and Delavar, M. R. (2008). "Potential Application of GIS to Layout of Construction Temporary Facilities." *International Journal of Civil Engineering*, 6(4), 235-245.

Sebt, M. H., Karan, E. P., and Eskrootchi, R. (2008). "Layout of Construction Temporary Facilities Using GIS." *Proc., CSCE 2008 Annual Conference*, 251-260.

Singh, V., Gu, N., and Wang, X. (2011). "A theoretical framework of a BIM-based multi-disciplinary collaboration platform." *Automation in construction*, 20(2), 134-144.

Sørensen, K. B., Christiansson, P., and Svidt, K. (2010). "Ontologies to Support RFID-Based Link between Virtual Models and Construction Components." *Computer‐Aided Civil and Infrastructure Engineering*, 25(4), 285-302.

Studer, R., Grimm, S., and Abecker, A. (2007). *Semantic web services: concepts, technologies, and applications*, Springer.

Teicholz, P. (2013). *BIM for Facility Managers*, John Wiley & Sons, New York, N.Y.

Törmä, S., Oraskari, J., and Hoang, N. V. (2012). "Distributed transactional building information management." *First International Workshop on Linked Data in Architecture and Construction*, Ghent University, 9-12.

Tserng, H. P., Yin, S. Y., Dzeng, R., Wou, B., Tsai, M., and Chen, W. (2009). "A study of ontology-based risk management framework of construction projects through project life cycle." *Automation in Construction*, 18(7), 994-1008.

Underwood, J., and Isikdag, U. (2011). "Emerging technologies for BIM 2.0." *Construction Innovation: Information, Process, Management*, 11(3), 252-258.

Underwood, J., and Watson, A. (2003). "An XML metadata approach to seamless project information exchange between heterogeneous platforms." *Engineering, Construction and Architectural Management*, 10(2), 128-145.

USGS (2013). "United States Geological Survey (USGS): Geospatial Semantics and Ontology." <http://cegis.usgs.gov/ontology.html>. (April 05, 2014).

Valcik, N. A., and Huesca-Dorantes, P. (2003). "Building a GIS database for space and facilities management." *New Directions for Institutional Research*, 2003(120), 53-61.

van den Broek, M., Brederode, E., Ramírez, A., Kramers, L., van der Kuip, M., Wildenborg, T., Turkenburg, W., and Faaij, A. (2010). "Designing a cost-effective CO< sub> 2</sub> storage infrastructure using a GIS based linear optimization energy model." *Environmental modelling & software*, 25(12), 1754-1768.

Van Deursen, D. (2010). "IFC2X3 ontology." <http://multimedialab.elis.ugent.be/organon/ontologies/IFC2X3>. (December 20, 2013).

Venugopal, M. (2011). "Formal specification of industry foundation class concepts using engineering ontologies." PhD thesis, Georgia Institute of Technology, Atlanta, GA.

Vos, N., van der Meijden, H., and Denessen, E. (2011). "Effects of constructing versus playing an educational game on student motivation and deep learning strategy use." *Computers & Education*, 56(1), 127-137.

Walker, J., Pan, E., Johnston, D., Adler-Milstein, J., Bates, D. W., and Middleton, B. (2005). "The value of health care information exchange and interoperability." *HEALTH AFFAIRS-MILLWOOD VA THEN BETHESDA MA-*, 24, W5.

Wang, C. C., and Xue, D. (2008). "Using domain ontology in a semantic blogging system for construction professionals." *Tsinghua Science & Technology*, 13, 279-285.

Wang, H.-H., and Boukamp, F. (2009). "Ontology-based job hazard analysis support." *International Workshop on Computing in Civil Engineering 2009*, ASCE Reston, VA, Austin, TX, 676-685.

Wang, H.-H., Boukamp, F., and Elghamrawy, T. (2010). "Ontology-based approach to context representation and reasoning for managing context-sensitive construction information." *Journal of Computing in Civil Engineering*, 25(5), 331-346.

Wu, I. C., and Hsieh, S. H. (2007). "Transformation from IFC data model to GML data model: methodology and tool development." *Journal of the Chinese Institute of Engineers*, 30(6), 1085-1090.

Yang, Q. (2003). "IFC-compliant design information modelling and sharing." *Journal of Information Technology in Construction (ITcon)*, 8, 1-14.

Yang, Q., and Zhang, Y. (2006). "Semantic interoperability in building design: Methods and tools." *Computer-Aided Design*, 38(10), 1099-1112.

Young, D. A., Haas, C. T., Goodrum, P. M., and Caldas, C. H. (2011). "Improving Construction Supply Network Visibility by Using Automated Materials Locating and Tracking Technology." *Journal of Construction Engineering and Management*, 137(11), 976-984.

Young, N., Jones, S., Bernstein, H. M., and Gudgel, J. (2009). "The Business Value of BIM-Getting Building Information Modeling to the Bottom Line." McGraw-Hill Construction, Bedford, MA.

Yurchyshyna, A., and Zarli, A. (2009). "An ontology-based approach for formalisation and semantic organisation of conformance requirements in construction." *Automation in Construction*, 18(8), 1084-1098.

Zhang, C., Li, W., and Zhao, T. (2007). "Geospatial data sharing based on geospatial semantic web technologies." *Journal of Spatial Science*, 52(2), 35-49.

Zhang, X., Liu, Y., and Zhang, X. "Characteristics of Railway Noise in Urban Area." *Proc., International Conference on Transportation Engineering*, ASCE, 1414-1419.

Zhong, B., Ding, L., Luo, H., Zhou, Y., Hu, Y., and Hu, H. (2012). "Ontology-based semantic modeling of regulation constraint for automated construction quality compliance checking." *Automation in Construction*, 28, 58-70.

Zhong, D., Li, J., Zhu, H., and Song, L. (2004). "Geographic information system-based visual simulation methodology and its application in concrete dam construction processes." *Journal of Construction Engineering and Management*, 130(5), 742-750.