Interoperability between BIM and GIS through open data standards: An overview of current literature

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Abstract. Building information modeling (BIM) allows representation of detailed information regarding building elements while geographic information system (GIS) allows representation of spatial information about buildings and their surroundings. Overlapping these domains will combine their individual features and provide support to important activities such as building emergency response, construction site safety, construction supply chain management, and sustainable urban design. Interoperability through open data standards is one method of connecting software tools from BIM and GIS domains. However, no single open data standard available today can support all information from the two domains. As a result, many researchers have been working to overlap or connect different open data standards to enhance interoperability. An overview of these studies will help identify the different approaches used and determine the approach with the most potential to enhance interoperability. This paper adopted a strong definition of interoperability using information technology (IT) based standard documents. Based on this definition, previous approaches towards improving interoperability between BIM and GIS applications through open data standards were studied. The result shows previous approaches have implemented data conversion, data integration, and linked data approaches. Between these methods, linked data emerged as having the most potential to connect open data standards and expand interoperability between BIM and GIS applications because it allows information exchange without editing the original data. The paper also identifies the main challenges in implementing linked data technologies for interoperability and provides directions for future research.

Keywords: BIM, GIS, Interoperability, Open data standards

1 Introduction

Building information modeling (BIM) and geographic information system (GIS) are technology-driven domains with important interrelation. BIM allows representation of data regarding all building elements [1] and it can support the planning, construction and operation of buildings. Meanwhile, GIS allows representation of spatial data regarding a certain environment including buildings [2]. This puts buildings at an intersection between BIM and GIS domains. A cooperation between these two domains is important to manage the built environment since the construction and operation of buildings affect their environment [3], and inversely, environmental aspects influence the planning, construction, and operation of buildings [4]. Benefits of such cooperation can include improved construction site safety, enhanced construction supply chain management, improved building emergency management, and sustainable urban design [3, 5-9].

BIM and GIS tools, however, have some significant differences that make collaboration a challenge. Originally, BIM tools were aimed at supporting the design of new objects with various levels of detail, while GIS tools were used to represent spatial data regarding objects that already exist in an environment [10]. Hence, they evolved differently [4]. They differ in data structure, in geometry representation, in level of development, and in the coordinate system they use [11]. As a result, even though the effort to integrate the two domains has been increasing in the past years [3], joining the domains remains a challenge. The objective of this paper is to investigate previous integration approaches and determine which of the approaches have the most potential to improve cooperation between BIM and GIS tools. The paper will also identify challenges and future research directions.

Amirebrahimi et al. [6] classified BIM and GIS integration levels into application level, process level, and data level integration. This paper will focus on data level integration through open data standards. The paper is structured as follows. In Section 2, we adopt information technology (IT) based definition of interoperability from international documents. In Section 3 we present some open data standards from BIM and GIS that can play a key role in interoperability between the two domains. No single open data standard, however, can fully support information exchange between BIM and GIS. Therefore, the data standards should be overlapped or connected with one another. And that will be the focus of Section 4 where previous approaches to connect open data standards are discussed. The accomplishments and shortcomings of these approaches will be presented in the same section. In Section 5 and 6 discussions and conclusions are presented along with challenges and future research directions.

2 Working definition of Interoperability

Interoperability is defined in different ways in different domains [12]. Therefore, we decided to adopt a well-established definition for interoperability before discussing the topic. Interoperability between software tools is an IT based concept. Hence, to establish a strong definition for the term, we decided to explore IT based definitions. For this purpose, we considered *IEEE Standard Glossary of Software Engineering Terminology* published by Institute of Electrical and Electronics Engineers (IEEE) [13] and *Information Technology – Vocabulary* jointly published by the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) [14]. ISO/IEC defines multiple types or features of interoperability such as syntactic interoperability, semantic data interoperability, and behavioral interoperability [15]. For this paper, we will use the general definition of the term given on ISO/IEC 2382:2015 to simplify the discussion. We also identified the definition of 'integration' and 'conversion' as these concepts are sometimes mistakenly used in interoperability discussions within the literature as being synonymous.

Table 1. Definitions of important terms based on international standards

Terms	IEEE [13]	ISO/IEC [14]
Interoperability	"The ability of two or more systems or components to exchange information and to use the information that has been exchanged".	The capability to communicate, or exchange data between different functional units in a manner that demands the user to have little or no knowledge regarding each unit
Integration	"The process of combining software components, hardware components, or both into an overall system".	"progressive assembling of system components into the whole system"
Conversion	"Modification of existing software to enable it to operate with similar functional capability in a different environment".	Changing "the representation of data from one form to another, without changing the information conveyed".

The IT based definitions presented in Table 1 articulate what interoperability is and what it is not. Interoperability is not conversion or modification of data representation. It is also not combining or assembling data models into one. Rather, we define it as the ability to communicate and exchange information between different software tools and use the information exchanged. The software tools, in this paper's context, are applications from BIM and GIS domains. This definition will be used as a requirement to evaluate interoperability approaches in this paper.

3 Interoperability through open data standards

There are different approaches to achieve interoperability between BIM and GIS tools. These approaches involve either reconfiguring the tools or modifying work processes or using open data standards [6]. This paper focuses on interoperability through open data standards. These open standards allow exchange of information between different software tools without requiring users to have a vendor specific software package [16].

The following subsections present some of the open data standards available for BIM and GIS and their capacity to go beyond their original scope and contribute towards BIM and GIS interoperability. The open data standards were selected by running a term co-occurrence analysis using VOSviewer on the 41 literatures referenced in this paper. The analysis identified CityGML (47 occurrences), IFC (31 occurrences), IndoorGML (22 occurrences) and LandInfra (8 occurrences) as open data standards with multiple occurrences.

3.1 CityGML

City Geography Markup Language (CityGML) is an XML-based data model widely implemented for the representation and exchange of 3D city models [17]. It is an Open Geospatial Consortium (OGC) standard that can represent built structures (buildings, tunnels, bridges, and roads) and environmental aspects (elevation, vegetation, water bodies and more) [18].

CityGML provides two concepts to support the exchange of features that are not explicitly represented in the schema [18]. One is the concept of generic objects and attributes. This concept allows features that are not explicitly represented in CityGML to be modelled using generic objects. The second concept is application domain extension (ADE) which allows addition of new features and information to existing CityGML classes without altering the semantic structure of CityGML [18, 19]. ADEs have played an important role in some of BIM-GIS collaboration efforts such as de Laat and van Berlo [20] and Deng et al. [21]. However, its use may not be supported by some software packages [20, 21].

Another important CityGML feature in BIM-GIS integration discussions is the concept of level of details (LODs). CityGML supports 5 LODs. At the lowest level there is LOD0 where buildings are represented by footprint or roof edge polygons. And at the highest level we have LOD4 where buildings are modeled with detailed elements including indoor space representations [18]. This concept supports integration efforts since features represented in similar LODs can be integrated more smoothly than features of different LoDs [22].

3.2 Industry Foundation Classes (IFC)

The Industry Foundation Classes (IFC) is an open source file format developed to enable interoperability between BIM software tools [16]. It is developed by buildingSMART International and it is the basis for ISO 16739-1:2018 [23]. Its data schema is defined in EXPRESS data specification language (defined in ISO 10303-11) and in XML Schema definition language (XSD) [24]. Currently, buildingSMART is working on IFC extensions to represent infrastructure facilities (such as railways, roads and bridges) which can enhance IFC's role in cross-domain collaboration between BIM and GIS tools [17].

3.3 IndoorGML

IndoorGML is another OGC open data standard and it is an XML-based schema for indoor spatial information [25]. Unlike IFC, which focuses on building component features, IndoorGML mainly focuses on representation of indoor space structures as well as interoperability between indoor spatial information tools [26]. It also provides extensive support for indoor navigation [27].

IndoorGML includes only a minimum set of geometric and semantic components to avoid overlapping with standards such as IFC and CityGML [25]. Therefore, it is beneficial to align it with these other standards [28]. IndoorGML permits such alignment by allowing referencing of objects in external datasets such as IFC and CityGML [25]. Through this referencing feature, IndoorGML has the potential to contribute to cross-domain collaboration between BIM and GIS tools.

3.4 LandInfra

LandInfra is a relatively new OGC standard [29]. It is a conceptual model for land and civil engineering infrastructure and it is published for predetermined use cases (facilities, projects, alignment, road, railway, survey, land features and land division) [30]. LandInfra has some potential overlap with CityGML. However, unlike CityGML, it does not have the concept of extension and LODs [29]. It does, however, support some features that are not available in CityGML nor IFC. These include: supporting subsurface data modeling, providing a framework to model legal information of buildings and storing survey related information [31].

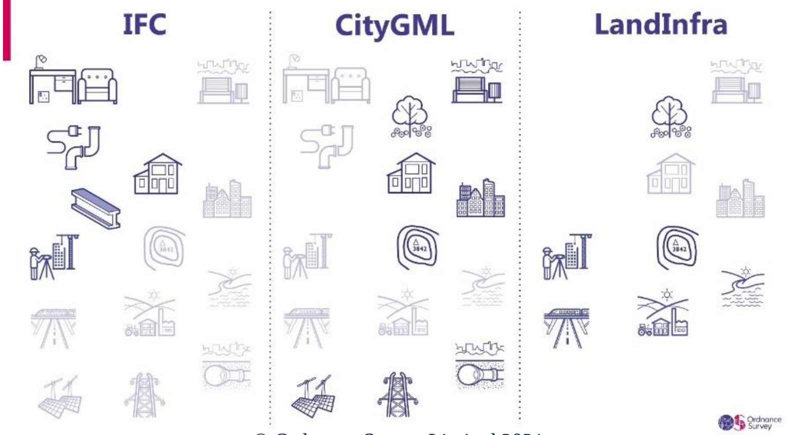

Fig. 1. Real-world objects represented by IFC, CityGML and LandInfra (Dark shading indicates strong coverage, light shading weaker coverage (or under development) and no shading implies no known coverage.) [32]

In summary, the open data standards presented in this section are developed with a specific scope in mind. IFC (currently) is for building information modeling, CityGML is for 3D virtual city modeling, IndoorGML is for indoor space modeling and navigation, and LandInfra is for land and civil engineering infrastructure. Figure 1 presents three of these data standards (IFC, CityGML and LandInfra) and various objects from BIM and GIS they support. As it can be seen in the figure, each standard supports only a portion of all the objects available. Although some of the standards have features that allow them to be extended beyond their original scope, no single standard can support all data exchange requirements between BIM and GIS. While interoperability does not necessitate complete data exchange, the lack of complete representation by the open data standard implies there exists data that cannot be exchanged using these data standards. As a result, researchers have been attempting to overlap or connect these open data standards with one another to improve data exchange between BIM and GIS.

4 Connecting BIM and GIS data standards

Previous studies that proposed different methods to connect open data standards from BIM and GIS are summarized in this section. Their contribution towards improving interoperability between BIM and GIS domains is discussed based on the definition of interoperability articulated in Section 2. The methods identified are categorized into *data standard conversion*, *data standard integration*, and *linked data approach* based on the process they implemented. It should be noted that some methods involved more than one of these processes.

4.1 Data standard conversion

Most of the previous BIM-GIS data standard integration methods focused on conversion of IFC to CityGML [3]. de Laat and van Berlo [20] proposed a unidirectional conversion where geometry of building objects and their properties (semantic information) stored in IFC format can be transformed to CityGML LOD4. Deng et al. [21] proposed a bidirectional exchange of geometrical information between IFC and CityGML as well as a unidirectional transformation of semantic information from IFC to CityGML. Both studies created new CityGML extensions (ADEs) to implement the conversion. These methods will work only if GIS applications are able to work with the new extensions which may not always be the case as revealed in the studies. A study by Donkers et al. [33] presented a unidirectional conversion algorithm to convert geometrical and semantic information from IFC model to CityGML LOD3 building model which does not include building interiors like CityGML LOD4. There was also a proposal to extract indoor building information from IFC into IndoorGML [34].

Some commercial software tools provide data conversion services, mostly from IFC to CityGML. Feature Manipulation Engine (FME) provides such service and it has been used by studies such as Yu and Teo [35] and Jusuf et al. [9]. Similarly ArcGIS and its data interoperability extension were used for conversion of BIM data into GIS data by studies such as Amirebrahimi et al. [6] and Tashakkori et al. [7].

Overall, the studies in this group proposed to exchange information between BIM and GIS by converting one data standard into another. The conversions are mostly unidirectional conversion from BIM to GIS (IFC to CityGML) which neglects the other half of the information exchange requirement that is from GIS to BIM. Moreover, even though some information can be transferred through conversion, the process alters and modifies the original data model. This results in data loss and inconsistencies [11, 17]. And the outputs are not always supported by the target software tools. Because of these drawbacks, the studies in this category fall short of meeting the requirements of interoperability established in Section 2.

4.2 Data standard integration

In this category, there are studies that propose aggregating both BIM and GIS data into a single unified model or database. A notable example is El-Mekawy et al. [8] who presented a unified building model (UBM) where all classes and concepts from IFC and CityGML would be aggregated. ArcGIS, a GIS software, was chosen to implement this model. When compared with methods that convert IFC into CityGML, the UBM method results in less information loss. However, the information exchange remains one directional, that is from BIM tools to GIS tools.

Wyszomirski and Gotlib [2] proposed to combine data from IFC and CityGML models and store it in a single database. The aim is to allow BIM and GIS tools to share information by sending and retrieving data to and from a database. However, BIM applications that are currently available on the market do not have mechanisms to work with data stored in a database.

The methods grouped in this section were able to reduce data loss by integrating IFC and CityGML data standards together instead of converting one into the other. However, whether fully integrating different models is favorable or not is questioned by some authors as it can create data ownership and intellectual property rights issues [11, 36]. Furthermore, the proposed methods favor GIS tools since those tools are the ones that get access to the integrated data. Therefore, methods in this group do not sufficiently satisfy the requirements of interoperability defined in Section 2.

4.3 Linked data for interoperability

Studies grouped in this category used linked data approaches to link BIM and GIS data standards. Hor et al. [37] proposed to link BIM and GIS through semantic web technologies by developing a semantic graph database framework using IFC and CityGML source datasets. They provided a web-based application to simulate the integrated model. However, practical use cases of the integration were not discussed in detail.

Vilgertshofer et al. [17] used a linked data approach to connect a BIM-based tunnel model with its corresponding GIS model by converting IFC and CityGML into web ontology language (OWL) representation and establishing a link between them. OWL is a language in semantic web technologies that is used to represent rich and complex knowledge [38]. Using OWL representation to establish the link allowed the authors to use semantic web querying language SPARQL to query data from IFC and CityGML.

Similarly, Karan et al. [10] proposed to create semantic web representation of BIM and GIS data , so that it can be processed by semantic web applications. They developed an ontological representation of IFC and linked that to selected existing GIS ontologies. The result was an extended ontology with concepts from BIM and GIS that were relevant to a specific use case (monitoring construction supply chain management). Then, using SPARQL, information could be retrieved from the combined dataset. The authors were able to represent the query results in ifcXML building model which can be loaded into BIM tools. They also used CSV format to represent the query result in GIS tools.

The studies categorized in this group developed a semantic web representation of BIM and GIS data standards and created a link between the web representation (rather than converting one data standard into another). Hence the original data remained unchanged. Only selected data was transferred instead of all the data. And the results could be created in formats that can be used by both BIM and GIS tools. These characteristics make the linked data approaches exceedingly favorable for interoperability use between BIM and GIS tools.

Semantic web approaches are gaining popularity in BIM-GIS collaboration researches [3]. Availability of BIM and GIS web standards can contribute to such studies. IFC schema is available in OWL ontology (ifcOWL) which provides the opportunity to represent building data in Resource Description Framework (RDF) graphs [1]. RDF is a framework used to publish and interlink data on the web [39]. Geospatial data can also be represented in the semantic web using standards such as GeoSPARQL and stRDF. GeoSPARQL provides a vocabulary for representation of geospatial data in RDF and it also defines a SPARQL extension to process geospatial data [40]. stRDF extends RDF with the ability to represent spatial and temporal data and it can be queried using stSPARQL which is an extension of SPARQL [41].

However, semantic web approaches have some critical issues. Ontologies developed by multidisciplinary professionals (BIM and GIS in the current context) may lead to inconsistency [10]. Establishing agreement between the different ontologies is a challenge [24]. Additionally, the technologies require some understanding of graph mathematics, graph databases structure and related tools in addition to understanding BIM and GIS knowledge data structure and schema characteristics [37]. And finally, the methods were implemented on limited use cases. Therefore, further studies that implement semantic web approaches to other use cases is necessary to better understand and evaluate these methods.

5 Discussion

This paper embraces an IT-based definition of interoperability extracted from IEEE and ISO/IEC standards. We defined interoperability as the ability to communicate and exchange information between different software tools and be able to use the exchanged information. Among the different methods that can be implemented to provide interoperability between BIM and GIS tools, the use of open data standards was the focus of this paper.

We presented some of the open data standards available in BIM and GIS (IFC, CityGML, IndoorGML and LandInfra) in Section 3. The interoperability role these standards play in their respective domain (For example CityGML in 3D virtual city modeling) and their capacity to extend beyond their original scope and support cross-domain collaboration between BIM and GIS tools (for example ADEs in CityGML) were discussed. However, currently, none of these standards can support all data exchange requirements between BIM and GIS. Even though interoperability does not necessitate complete data exchange, the lack of complete representation by the open data standard indicates that there exists data that cannot be exchanged while using these data standards. Therefore, to enhance interoperability, the data standards could be overlapped or connected with one another.

Several studies have proposed several approaches to connect BIM and GIS data standards. These proposals were grouped into three in this paper. The first group proposed to convert one data standard into another. Some information could be transferred between BIM and GIS tools through these conversion methods. However, the conversion process alters and modifies data representation resulting in data inconsistency and data loss. Moreover, most of the conversion methods are unidirectional transformations (from BIM to GIS) that cover only one side of the information exchange requirement. And at times, the outputs were not supported by the target applications. Hence, these approaches fail to correspond with the definition of interoperability established in Section 2 of this paper.

The second group of approaches proposed to combine data standards from BIM and GIS domains (in IFC and CityGML format) and store it in a unified model or database. These methods allow information from BIM and GIS domains to be aggregated and stored together. However, it was the GIS tools that had access to the aggregated data. That means data is transferred from BIM to GIS but not vice versa. Therefore, these methods fell to meet the requirements of interoperability established in this paper.

The third group of BIM-GIS interoperability studies identified were studies that created links between different data standards through linked data and semantic web technologies. This approach allows different models to remain separate and stored in their original form while selected information is shared between them without loss of meaning [11]. The outputs could be given in formats that are supported by both BIM and GIS tools. These important characteristics of linked data approaches complies with the definition of interoperability adopted in Section 2 of this paper.

Although semantic web technologies are identified as promising methods to link data models, they still have certain issues. Establishing agreement between different ontologies from different disciplines is a crucial challenge [24]. One way to address this issue could be through formalization of AEC ontologies [10]. Currently, there are discussions as to whether to create a central ontology and build everything else around it or manage data in a completely decentralized manner [24]. Another challenge is that these technologies require some understanding of graph mathematics, graph database structure and related concepts [37].

6 Conclusion

The relationship between buildings and their surrounding environment calls for a collaboration between BIM and GIS domains. BIM supports the design, construction, and operation of the buildings while GIS supports spatial data regarding the surrounding of those buildings as well as their inside space. Interoperability between software tools from the two domains will allow us to combine their functionality and leverage it for better management of the built environment.

To discuss interoperability between BIM and GIS tools, it is necessary to have a well-developed definition of interoperability. Hence, this paper began by adopting a definition of interoperability from IEEE and ISO/ IEC standards. Then, between the different approaches towards interoperability, this paper focused on the use of open data standards. Some open data standards from BIM and GIS were presented and their potential to support cross-domain interoperability between BIM and GIS was discussed. However, since none of the open data standards support all necessary data exchange requirements, they need to be overlapped or connected with one another to improve interoperability.

There were many approaches in the past to connect open data standards from BIM and GIS. These approaches were summarized in this paper and were classified into data standard conversion, data standard integration and linked data approach. Among these, the use of linked data methods to create a link between BIM and GIS data standards was identified as a promising approach to enhance interoperability for the fundamental reason that it allows information exchange without editing the original data. However, harmonization between knowledge bases created by different domains remains a challenge to the linked data methods. Furthermore, additional use case-based studies that implement linked data methods to exchange information between BIM and GIS tools are necessary to further understand the role linked data methods can play in the interoperability discussion.

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