Semantic interoperability between BIM and GIS – review of existing standards and depiction of a novel approach

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Abstract

When it comes to Big Data ecosystems, main technical challenges pertain to defining links between data, information and knowledge, thus reaching interoperability. Interoperability issues are addressed in the context of data curation related tasks. Interoperability is a major pre-requisite for achieving data automation, validation, thus fighting counter-productiveness (notably through data incentivisation). The demand for interoperable, reusable and open data is more and more present, thus pushing forward the research for innovation data curation approaches. This article gives a high-level description of our approach for bridging the interoperability gap among GIS (Geographic Information Systems) and BIM (Building Information Modelling) systems. After a summary of standards existing in the considered application domains, we further specify the interoperability issues applying and present existing approaches for reaching interoperability among models. Based on the study of these approaches, we then discuss our approach and the related multi-scale modelling. We illustrate how it allows reaching federation among GIS and BIM systems, while supporting consistent reasoning on the features of the federated systems. We conclude with a listing of future work to be done in order to reach this vision.

Keywords: BIM, GIS, Semantic Interoperability, Cyber-Physical Systems, Granularity

1. Introduction

Today's urban scopes come with overwhelming challenges that concern multiple stakeholders or territorial communities. Thus, we are witnessing more collective practices along with innovative rules and norms aiming to conceive multi-level, multi-scale solutions addressing those challenges associated with the vision of smart cities. More specifically, when considering knowledge automation, smart cities become sandboxes for problem-solving, where numerous dimension such as spatial economic, social, aspects should be taken into consideration to provide answers to local challenges: climate change, energy efficiency, etc. Complexity is pushed at an even higher level when taking into consideration the different standards and regulations that apply on each of the aspects listed above. Notably, regarding spatial aspects there are two main standard families that apply: a) Standards pertaining to Building Information Modelling (BIM), promoted by buildingSmart International (bSI) and the ISO TC 59 b) Standards pertaining to Geographic Information Systems (GIS), promoted by the Open Geospatial Consortium (OGC) and ISO TC 211. While GISs allow integrating of geographic information, BIM aims to management building information throughout its lifecycle (e.g. from design to demolition). While both standard families come with structured information models and processes for describing aspects from the considered domains, no links have been defined between the two worlds. Thus when it comes to implementing knowledge automation approaches in the context of smart cities, data must be seamlessly integrated into a system ensuring its consistent interpretation by the machine. For addressing this issue, we present our approach for interoperability, based on federation meta-model. The article is divided as follows: section 2 introduces BIM and GIS information models as defined in the respective standard families, section 3 ,4 introduce related work and a review of existing standard approaches for interoperability, while section 5 describes BIM and GIS barriers. Our approach is discussed in section 6 and finally we conclude in section 7.

2. The need for interoperability

2.1 BIM information model

Building Information Modelling (BIM) is a 3D model-based process that gives architecture, engineering, and construction professionals the insight and tools to more efficiently plan, design, construct, and manage buildings and infrastructure. BIM model can be used for analysis to explore design options and to create visualizations that help stakeholders understand what the building will look like from start to finish. Finally, BIM describes a method of work by which all relevant information for the life cycle of the building is integrated, administered and exchanged among the project participants. ISO 29481 (*ISO 29481-1: Building information models - Information delivery manual - Part 1: Methodology and format*, 2016, p. 294) defines BIM as a shared digital representation of an object built to facilitate design, construction and operating process and form a reliable basis for decision-making. The first stage of BIM standardization was carried out in 1999 by IAI (now buildingSmart International) (Wang, 2012) . BIM relies on the following international standards:

- Information Delivery Manual (IDM) specifies how information is exchanged in a process. It is based on the ISO 29481 standard and is defined as an interchange agreement. IDM is a natural language description of the exchange.
- Model View Definition[1] (MVD) describes the data model needed to meet the exchange requirements described in the IDM. The underlying methodology is described by Part 3 of ISO 29481 (ISO 29481-3: Building information models - Information delivery manual - Part 3: Model View Definition., 2010, p. 294).
- Industry Foundation Classes (IFC) (Liebich et al., 2013) represent the conceptual model for buildings and comprises all classes and relations for representing a building (ISO 16739: industry Foundation (IFC) for data sharing in the construction and facilities management, 2013, p. 167) The IFC model is specified in EXPRESS and complies with ISO 10303 (ISO 10303: Industrial automation systems and integration -- Product data representation and exchange -- Part 21: Implementation methods: Clear text encoding of the exchange structure, 2016) also called STEP part 21 (Standard for the Exchange of Product model data). STEP focuses on the representation and exchange of product data and aims to integrate the processes of design, development, manufacture, and maintenance (see figure 1).

2.2 The GIS standard family

GIS allows capturing, storing, handling and analysing geographical data (Sahoo, 2017). The main international organization developing standards for geospatial information is ISO TC 211. It specifies methods, tools, and services for data management, acquisition, processing, accessing, presenting, and transferring such data digitally (*ISO 191xx series of geographic information standards- Concepts and organization of the reference model defined in ISO standard 19101*, 2005). The approach to conceptual modelling in the ISO 19100 series is based on the principles described in the ISO CSMF (Conceptual Schema Modelling Facilities). This conceptual schema includes four levels: metamodel, conceptual (abstract) schemas, conceptual (applications) schemas and implementation schemas (see figure 2). The first level contains the General Feature Model defined in ISO 19109, which specifies the concepts, terminology, operations, and assumptions needed to build the basic constructs in the Conceptual Schema layer level. The contents of the meta-meta model level is usually expressed in natural language and is not itself subject to standardization. Conceptual Schema layer contains the definitions of the concepts, terminology, operations and assumptions needed to construct application schemas.

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[1] http://www.buildingsmart-tech.org/specifications/mvd-overview

Application schemas define the types of features and processes that are instantiated to produce datasets of geographic information. Application schemas are expressed using syntax and semantics from one or more conceptual schemas. The "bottom" layer contains the actual data that is defined by the application schema at the application model level.

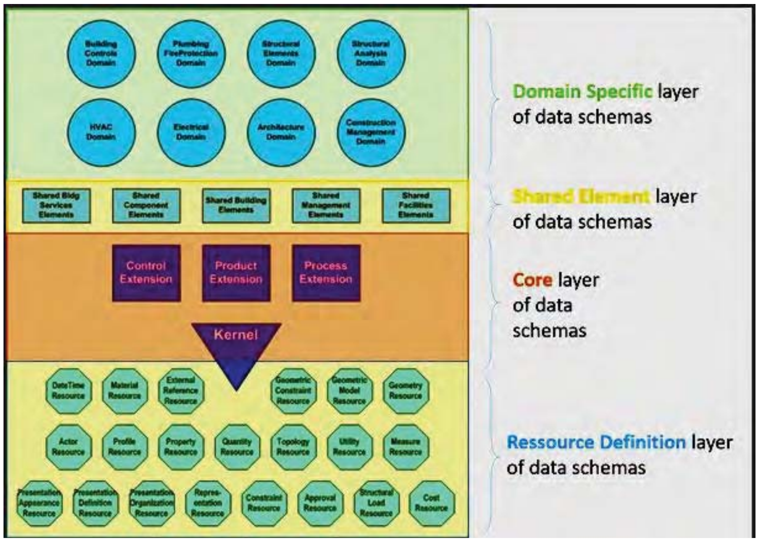


Figure 1: IFC layers of data schemas (ISO 16739-1) and modelled in the EXPRESS Schema (ISO 10303-11).

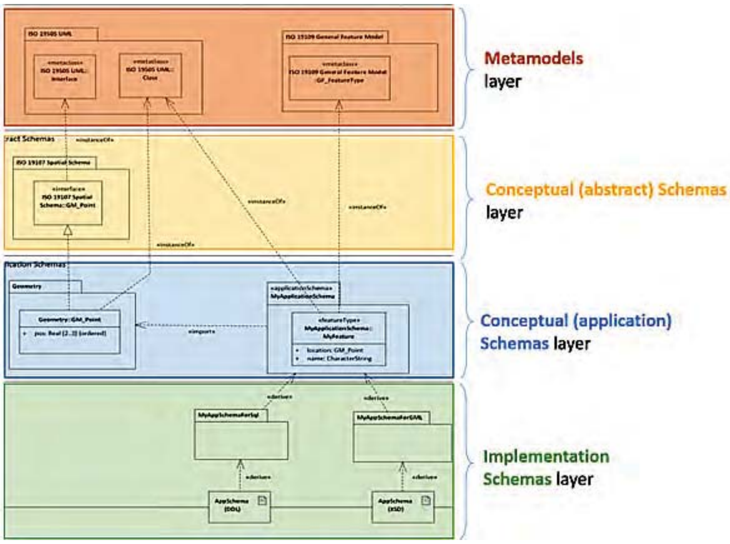


Figure 2: ISO TC 211 Conceptual model (ISO 191xx series 2006)

3. Related Work

In this section we are presenting previous work done to achieve BIM and GIS interoperability: (Deng, Cheng, & Anumba, 2016) presents a framework that can achieve automatic data mapping between IFC and CityGML in different level of details (LOD), using a reference ontology. However, the study only achieved bidirectional mapping for the building models. (Mignard & Nicolle, 2014) introduces a semantic extension called Urban Information Modelling (UIM), that defines spatial, temporal and multi-representation concepts using extensible ontology. However, the main drawback of this approach persist in the usage of database to store the instances of the ontology. (Hor, Sohn, Claudio, Jadidi, & Afnan, 2018) solves the interoperability between BIM and GIS by applying the following steps: 1) transforming IFC to RDF, 2) transform GIS to RDF, and finally 3) using the GMO algorithm to map between the Ontologies. However, the algorithm needs more enhancement as it does not take into count all semantic information. (Floros, Pispidikis, & Dimopoulou, 2017) presents a methodology to transform the IFC model into CityGML as a potential way to achieve interoperability between GIS and BIM. However, the methodology presented did not investigate a fully complex model, and many semantic information was lost in the process. Our study and research focus on connecting BIM and GIS domains while keeping them independent from each other (federation approach) which is different from the previous approaches presented. In the next section we are going to present the challenges and approaches we are going to adapt to solve interoperability between the two domains.

4. The need for interoperability

4.1 The concept of interoperability and its flavours

Several definitions exist for interoperability concept: the ISO alone holds more than a dozen standards, each coming with its own definition of "interoperability". Interoperability is defined as the "capability to communicate, execute programs, or transfer data among various functional units in a manner that requires the user to have little or no knowledge of the unique characteristics of those units". This definition implies that interoperable systems can either exchange information or be accessed with a single method. In order to further specify and tackle the interoperability issues among BIM and GIS, we follow the General System Theory (GST) abstraction (Von Bertalanffy, 1969) and adapt it to the previous definition of CSPs. We thus consider BIM and GIS abstracted as systems comprising several parts, each part exhibiting some behaviour (that can be different from the overall system's behaviour). These behaviours and their related components, mechanisms and processes are monitored, managed and coordinated by some computer. Hence interoperability is achieved using standards that enable behaviours of parts of the system and the overall behaviour of the system to cooperate seamlessly in order to reach a common goal or function. With these definitions and statements in mind, the next sections present existing levels of interoperability and discuss existing standard approaches for implementing interoperability.

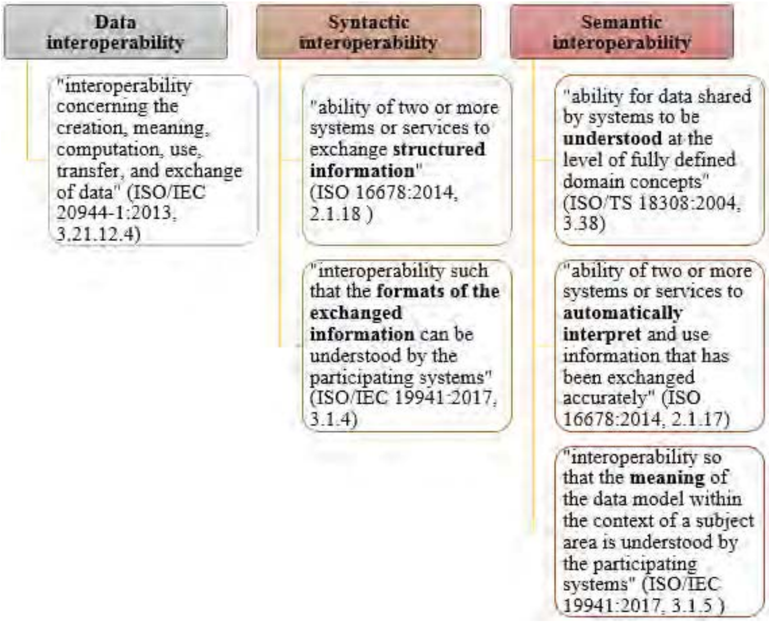
4.2 Levels of interoperability

Existing standards identify three main levels of interoperability, namely: data, syntactic, and semantic interoperability. These layers are connected and build upon each other, lower levels providing elements required by upper levels functionalities (Kubicek, Cimander, & Scholl, 2011). Figure 3 illustrates those levels along with their definitions as pertaining to ISO standards. Sometimes referred at as physical interoperability, the issues pertaining to the data level of interoperability have been long resolved with the adoption of hardware standards such as Ethernet (Hollenbeck, n.d.); along with standard protocols for lower layers of the ISO network architecture e.g. TCP/IP ((Postel, 1981a) (Postel, 1981b)) and HTTP ("Hypertext Transfer Protocol -- HTTP/1.1," n.d.). Syntactic interoperability addresses the syntax of messages exchanged among CSPs considered artefacts. The related issues have been resolves through the adoption of XML and related syntax standards e.g. HTML, WSDL ("Web Service Definition Language (WSDL)," 2011) and SOAP ("SOAP Specifications," n.d.). Semantic interoperability addresses the meaning of the messages exchanged and related issues have not yet been resolved by existing standards and approaches. Semantic Web standards and languages allow specifying such meaning, by means of formal and explicit specifications of conceptualisations e.g. ontologies. Considering the different Semantic Web languages existing, semantic interoperability comes with different flavours:

- Minimum semantic interoperability is enabled by the use of RDF ("RDF - Semantic Web Standards," n.d.) and allows specifying the minimum knowledge than can be exchanged through a sentence e.g. what is expressed through the sentence itself. Such low level of semantic interoperability requires further manual and/or automated handling of the exchanged data.

- *Extended* semantic interoperability allows defining a minimal ensemble of beliefs onto which two computer agents agree. Such ensemble of beliefs allows computer agents to make new deductions from the implicit facts contained in the message they exchange. Such level of semantic interoperability is enabled by the use of RDF Schema ("RDF Schema 1.1", n.d).
- *Full* semantic interoperability is enabled by the usage of the OWL ontology language family. An OWL shared ontology can specify what computer agents may agree upon, while preventing them from making erroneous deductions. It allows specifying a knowledge conceptualization bounded to a given domain.

Following these definitions, semantic interoperability denotes the ability of applications and business partners to interpret exchanged data in a consistent way, implying explicit and formal structures. Even though, ontologies are explicit specifications of shared conceptualisations of a knowledge (Studer, Benjamins, & Fensel, 1998), relying on it doesn't lower semantic heterogeneity of the so conceived knowledge models. Even if, these ontologies have been defined, they are independently from one another, with no semantic links formed to identify and align concepts and relations between those ontologies. Thus, no consistent interpretation can be delivered based on those ontologies solely. The need for defining links among existing knowledge models pertaining to BIM and GIS becomes urgent. And for doing so, the same approaches used for coupling models can be applied to ontologies. In this context, the ISO standard about the integration of industrial automation systems (*ISO 14258: Industrial Automation Systems- concepts and rules for enterprise models*, 1998) defines three possibilities: models can be *integrated*, *unified* or *federated.* These three types of approaches were more recently considered as standard interoperability approaches in the context of ISO 11354, defining the Enterprise Interoperability Framework or EIF (*ISO 11354-1: Advance automation technologies and their applications – Requirements for establishing manufacturing enterprise process*, 2011). The sections below further discuss these three approaches, notably based on their specification in the EIF.


Data interoperability

"interoperability concerning the creation, meaning, computation, use, transfer, and exchange of data" (ISO/IEC 20944-1:2013, 3.21.12.4)

Syntactic interoperability

"ability of two or more systems or services to exchange **structured information**" (ISO 16678:2014, 2.1.18)

"interoperability such that the **formats of the exchanged information** can be understood by the participating systems" (ISO/IEC 19941:2017, 3.1.4)

Semantic interoperability

"ability for data shared by systems to be **understood** at the level of fully defined domain concepts" (ISO/TS 18308:2004, 3.38)

"ability of two or more systems or services to **automatically interpret** and use information that has been exchanged accurately" (ISO 16678:2014, 2.1.17)

"interoperability so that the **meaning** of the data model within the context of a subject area is understood by the participating systems" (ISO/IEC 19941:2017, 3.1.5)

Figure 3: Levels of interoperability

4.3 Standard Approaches for Semantic Interoperability

In the context of an ***integrated approach***, all exchanged elements have to be represented with respect to a common form. Such common form must have an associated level of expressiveness allowing to capture the specific details of the elements exchanged, especially those impacting interoperability. All elements and artefacts in the considered system or organization have to be described according to the common form, even if the latter isn't built upon an existing International standard. This approach is suitable when designing and implementing new systems rather than when reengineering existing systems for interoperability (Métral, Billen, Cutting-Decelle, & van Ruymbeke, 2010t). An example of ISO standards implementing model integration are the "Industrial automation systems and integration — Product data representation and exchange" (*ISO 10303: Industrial automation systems and integration -- Product data representation and exchange -- Part 21: Implementation methods: Clear text encoding of the exchange structure*, 2016). ***Unified approaches*** require a common meta-model. In its simplest version, such meta-model can be a reference vocabulary, while in a more advanced version it can represent a complete ontology. Defined as a meta-model, it allows establishing semantic equivalences among considered concepts or entities. All other considered models with their related syntaxes and semantics have to be mapped to the common meta-model. Using the common meta-model, a translation between the constituent models is possible even though they might encounter loss of some semantics or information (*ISO 11354-1: Advance automation technologies and their applications – Requirements for establishing manufacturing enterprise process*, 2011). Example of ISO standards implementing unified model are TC184 "Industrial data" (SC4) and "Interoperability, integration and architectures for enterprise systems and automation applications" (SC5) sub-committees. ***Federated approaches*** implies that no partner imposes their models, languages, or methods of work. Such approaches do not imply a common form or a common meta-model (*ISO 11354-1: Advance automation technologies and their applications – Requirements for establishing manufacturing enterprise process*, 2011). They mainly apply to contexts where the entities considered for interoperability rely on too different or too complex vocabularies or methodologies. In a federated approach, each entity needs to adapt its processes and methods. For reaching interoperability in such a context, mappings must be specified among input and output information of the considered entities or artefacts. Remaining inconsistencies must be manually addressed. Implementing successful federation among organizations or systems comes with more challenges than the two previous approaches. As an example of such implementation, we may cite the federation approach in ISO 16100 "Manufacturing Software Interoperability Services" (ISO 16100: Industrial automation systems and integration -- Manufacturing software capability profiling for interoperability, 2011, p. 161).

5. Bringing semantic interoperability between BIM and GIS

While BIM comes with detailed 3D visualization and various functionalities to organize and manage huge volumes of data related to buildings, GIS environments are highly customizable, well-equipped for multi-dimensional analysis, and ideal for projects involving multi-site environments. Even though one is usually struck by the differences among the methods and processes, there is a general tendency of combining them in order to benefit from their cumulated advantages. As both domains are complimentary to each other, reaching interoperability would bring highly productive outcomes in the field of digital AECO (Architecture, Engineering, Construction and Operations). However, reaching such vision comes with several challenges, the main ones being listed below:

1. Coordinate systems and spatial referencing: GIS use two-dimensional real-world coordinates (RWC 9), while BIM systems use three dimensional relative coordinates between objects, with a reference to RWC at root object. GIS is based on a global spatial reference system and use boundary representation. BIM applications use local spatial reference systems.
2. Temporal aspects: In BIM applications, a building object is characterized by its geometrical representations and its geometrical and non-geometrical properties. Such object can have several geometrical representations, as they each correspond to a different point of view. Still, the BIM standards do not define any links between these geometrical representations and geometrical properties of the considered building object. Initially such permissiveness was wanted for BIM applications (in order to cope with how levels of detail are handled in GIS systems). But today, standards should restrict or specify explicitly the possible choices. The level of permissiveness allowed by today's standards hinders the efficient implementation of BIM ecosystems, as it all depends of the choices made at the level of software implementations

3. Semantics: BIM and GIS use different vocabularies to describe their entities and properties. No equivalencies have been defined among these elements. While bSI and there is no define link between the IFC and GIS vocabulary has developed the bSDD (buildingSmart Data Dictionnary) listing all existing terms and properties in the IFC standard, there are no explicit links defined between the bSDD vocabulary and other similar initiatives such as the French standard XP P07-150 (AFNOR PPBIM), promoted in the context of CEN/TC 442 WG4. Such semantic links are essential for implementing consistent information exchanges based on the IFC format.

6. Achieving BIM/GIS semantic interoperability

Considering the above approaches, along with our application context e.g. knowledge automation in smart cities, approaches based on federation appear as the most suitable. Indeed, integrated approaches imply using one single common model according to which all other models are conceived and interpreted. As mentioned above, these approaches are best suited when engineering novel CPSs, and fail in addressing all subtleties of existing CPSs. More specifically, in the context of our approach, two axes are considered for federation - horizontal, and vertical. For the first case, we consider relying on an existing approach namely the federated architecture for OWL ontologies or FOWLA (de Farias, Roxin, & Nicolle, 2015). For the latter, Hobbs' granular partition theory (Hobbs, 1985) gives several interesting perspectives and future work directions. Both approaches are discussed in the sections below. Following the database federation approach (Sheth & Larson, 1990), FOWLA is an approach relying on SWRL rules for federating autonomous ontologies (including TBox and ABox). The architecture contains two main components: The Federal Descriptor and the Federal Controller (de Farias, Roxin, & Nicolle, 2015). The first is responsible of identifying missing concept instantiations and identifying new alignments (based on previously defined ones). The latter is mainly responsible of executing SPARQL queries. More specifically, it comes with a Rule Selector module that is responsible of selecting only the subset of SWRL rules that allow returning results pertaining to the considered SPARQL query. Granularity is the extent to which a system is composed of distinguishable pieces or grains. It can either refer to the extent to which a larger entity is subdivided, or the extent to which groups of smaller indistinguishable entities have joined together to become larger distinguishable entities. For example, a kilometre broken into centimetres has finer granularity than a kilometre broken into meters. Information granules, as the name itself stipulates, are collections of entities, usually originating at the numeric level, that are arranged together due to their similarity, functional adjacency, indistinguishability, coherency or alike (Pedrycz and Bargiela, 2002). In order to best understand how this can be applied to our context, let us take an example. Consider planning a trip. In this case, the route one has to travel can be abstracted as a one-dimensional curve. When considering an infrastructure use case involving for example works on the asphalt on the road, one can no longer approximate the road as a curve, but has to take into account its volume – it thus becomes a 3D volume. With the indiscernibility relation previously defined, one can identify predicates pertaining to the use cases considered. In the first one, two points in the asphalt, identified through their respective coordinates will be undiscernible. An example of a predicate pertaining in the context of this first use case would be the distance between one point on the road and the destination point. Granular computing is an approach orthogonal to existing modelling approaches. It allows separating one knowledge domain into smaller pieces of knowledge, by means of consistent and structured methods, thus building a granular perspective. This allows consistent reasoning on these smaller pieces of knowledge but also on the whole knowledge domain. Still, while several formal models of granularity have been defined in literature (Mani, 1998), (Keet, 2008), the different granular perspectives have to be explicitly and formally defined, with regard to the considered application domain. Moreover, in applications involving context awareness, one has to further study and specify the relation between knowledge granularity and context granularity. Given the above considerations, a first step in our approach addresses consistent semantic modelling of BIM and GIS information. Together with experts from the domain of BIM and GIS, the next steps of our work will investigate what alignments can be defined among BIM/GIS concepts and models (as defined in the respective ISO TC 211 and IFC ontologies). As such, the rules defined in the (ISO 191xx standard family for application schemas (*ISO 19109: Geographic information- rules for application schema*, 2015, p. 109) and feature catalogues (*ISO 19110: Geographic information -- Methodology for feature cataloguing*, 2016) allow to represent IFC by means of UML. But as UML is not formal, additional alignments have to be investigated. More specifically, our future work will consider the following levels of alignments:

- Alignments among metamodels: General Feature Model (GFM) of ISO 19109 has to be compared with the IFC elements contained in the core layer of data schemas of the IFC schema. IFC classes such as IfcKernel, IfcControlExtension, IfcProcessExtension, IfcProductExtension have to be mapped to their equivalents in ISO 19109 GFM.
- Alignments among abstract conceptual GIS schemas and data schemas contained in the Resource Definition layer of IFC: Several geometry and topology elements from the GIS temporal schema (ISO 19107: Geographic information -- Spatial schema, 2003) are equivalent to sub-classes of IfcDateTimeResource or IfcTopologyResource. Also several elements from ISO 19107 Temporal schema have equivalents in the IFC terminology notably subclasses of IfcGeometryResource and IfcPresentationAppearanceResource. IFC classes such as IfcGeometricConstraintResource or IfcGeometricModelResource have to be mapped to their equivalent concepts in spatial referencing (ISO 19111: Geographic information -- Referencing by coordinates, 2019).
- Alignments among application schemas in GIS and domain specific and shared elements IFC data schemas: IFC classes such as IfcKernel, IfcControlExtension, IfcProcessExtension, or IfcProductExtension have to be mapped to their equivalent concepts in ISO 19109 GFM. Concepts from the IFC Shared Elements layer of data schemas have to be mapped to their respective equivalents in ISO 19130 (ISO/TS 19130: Geographic information - Imagery sensor models for geo-positioning, 2010).

With the above considerations in mind, future work to be done in the context of this approach also involves the following items:

- Missing ontologies: for example, which ontology mediation will be used to establish compatibility on terminological level
- Missing links: some can be identified fairly easily, others require exchanges with business experts and are more complex to define.
- Granular approaches impact: the concept of granularity, seems intuitive and easy to implement, however the manner of ontologies, the associated levels and perspectives must be explicitly and formally specified by integrating the characteristics of the domain of knowledge concerned (Livi & Sadeghian, 2016)
- In addition, when it comes to integrate granularity into application that handle business knowledge it is necessary to investigate, define and specify the granularity if knowledge and it is context.

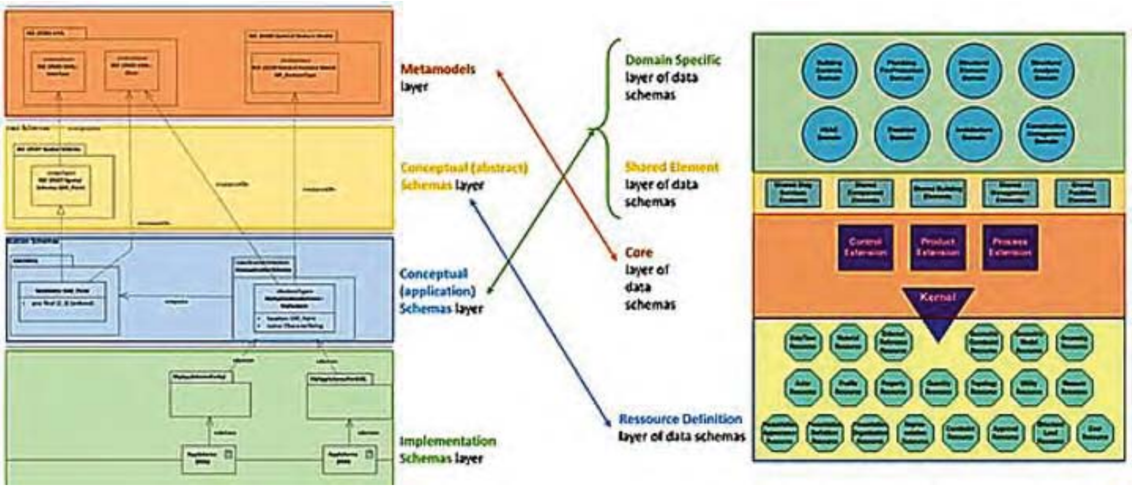


Figure 4: Links among the layers of the information models considered

7. Conclusion

Previous studies aim to integrate BIM to GIS or vis versa. However, our object aims to remove the barrier that exists between the two domains based on their standards and keep them independent from each other. In this article we aim at defining the interoperability issue among GIS and BIM systems, and specifying an approach addressing this issue. Our approach relies on Semantic Web technologies and granular approaches for performing two-axis federation. In our approach, we do not seek to merge BIM and GIS, neither to promote one over the other, hence we intend to reuse the FOWLA approach and its advantages in terms on lightly-coupled ontology federation. Granular approaches further help in conceiving and managing different abstractions of the same context or scape, which is highly pertaining to the urban environments considered by our application domain. The purpose of achieving interoperability between BIM and GIS is to specify and implement means to describe buildings along with their environment, at different scales.

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