Linking BIM and GIS Standard Ontologies with Linked Data

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Abstract. Following the analysis of existing BIM and GIS standards, formats, differences in the interpretations of the underlying concepts have been identified. Still, in each of the two considered domains several ontologies have been defined for these terms without seeking an alignment among their definitions. With this scope in mind, this article presents several mappings expressed by means of explicit semantic links between GIS concepts (as present in the related ontologies for the ISO 191XX standard family) and BIM concepts (as represented in the IFC standard ISO 16739:2018). Such semantic mappings are defined in order to ensure a knowledge continuum between both domains, thus enabling seamless reasoning in application contexts spanning over them e.g. urban contexts.

Keywords: BIM, GIS, Semantic Web Technologies, Ontologies, ISO standards, Linked Data.

1 Introduction

Building Information Modeling (BIM) and Geographical Information Systems (GIS) both address modelling of environments: traditionally GIS focus on natural environment, whereas BIM targets built environments. Developed until now independently, both domains are addressed by different standards. Following " Building information models — Information delivery manual — Part 1: Methodology and format" (ISO 29481-1: 2016) [16], BIM is defined as a shared digital representation of physical and functional characteristics of any built object (including buildings, bridges, roads, etc.) which forms a reliable basis for decisions . According to "Geographic information — Reference model — Part 1: Fundamentals" (ISO 19101-1:2014) [10], GIS is an "information system dealing with information concerning phenomena associated with location relative to the Earth". Being initially conceived with different purposes, BIM and GIS differ in granularity: while BIM handles building information with a high degree resolution, GIS handles data about natural environments along with man-made structures with a lower level of detail. Today these frontiers seem to vanish as decision-support systems for urban environments, public sector or even disaster management need to combine their features and advantages to improve quality of service. For example, to help new students arrive to their classes quickly and efficiently we need to connect outdoor navigation (supported by GIS) and building (university) indoor navigation (supported by BIM). To guarantee information continuity that can place buildings in urban context by adding its characters, analytic capability and impact in urban environment we need to ensure seamless data interpretation between both domains. Such data interpretation is ensured by transforming data into knowledge by means of Semantic Web approaches e.g. ontologies. Being an explicit and formal conceptualization, an ontology has the benefit of ensuring computer-reasoning, thus interpreting data instances according to an ensemble of rules. Still, ontologies on their own do not resolve the interoperability issue mentioned before e.g. the need for seamless interpretation across both domains. Following the Linked Data principles [1], vocabulary links must be defined among terms specified in different ontologies. While several ontologies have been defined in both domains, they have all been specified independently from each other and nor so many links and mappings have been defined among them. In the context of this article, we are solely aiming at standard ontologies in BIM and GIS domains, which are the ifcOWL ontology for IFC [22] and the ontologies defined by ISO/TC 211 for the ISO 19100 standard family (https://github.com/ISO-TC211/ontologies). Following a summary of technologies and standards encompassed by BIM and GIS domains, we present existing BIM and GIS ontologies (sections 2 and 3) along with previous mapping approaches among these ontologies (section 4). Section 5 presents the links we identified for these ontologies: concepts and properties. Section 6 discusses those links and concludes the article.

2 BIM and existing standard ontologies

2.1 Building Information Modeling (BIM)

BIM is the process of generating, storing, managing, exchanging, and sharing building information [8] in an open format, namely IFC. BIM focuses on the creation of virtual 3D models that can be explored and modified by all the stakeholders involved in a construction project. At the level of the ISO, it is the Technical Committee ISO/ TC 59/SC 13 "Organization and Digitization of information about buildings and civil engineering works, including building information modelling (BIM)" that is in charge of developing BIM-related standards. Three main ISO standards exist for BIM: (1) Information Delivery Manual (IDM) (ISO 29481-1:2016) [16], (2) Model View Definition (MVD) ("Building information models — Information delivery manual — Part 3: Model View Definition.") (ISO 29481-3:2010) [17], and (3) Industry Foundation Classes (IFC) ("Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries") (ISO 16739:2018) [9]. A stakeholder specifies in natural language his requirements in the form of an IDM. This is translated into an MVD which represents a subset of the full IFC schema corresponding exactly to the requirements specified by the stakeholder. The IFC standard both comes with a data schema (defined in both EXPRESS and XML) and exchange file structures (clear text encoding of the exchange structure according to ISO 10303-21 and XML). Thus, BIM data is exchanged among stakeholders in the form of IFC files. For example, an architect creates an architectural model exports it in IFC version and shares it with an HVAC engineer. The HVAC engineer references the file and uses it for coordination or energy analysis. However, the HVAC engineer cannot modify the content provided by the architect (e.g. add a new wall): he/she needs to ask the architect to make these changes. For augmenting the efficiency of IFC-based exchanges and workflows, an MVD must be defined; e.g. definition of the specific IFC data schema subset pertaining to a given data exchange requirement for a specific software application. MVDs allow checking that the IFC data exchanged is conform to the exact requirements of the workflow considered. IFC data is structured into four different layers: (1) The *resource layer* includes all individual schemas containing resource definitions, used in BIM project (e.g. IfcAddress, IfcReference); (2) The *core layer* contains the most general entity definitions as the kernel schema (e.g. IfcActor) and the core extension schemas IfcProcessExtension (e.g. IfcEvent), IfcProductExtension (e.g. IfcBuilding), IfcControlExtension (e.g. ifcPerformanceHistory); (3) The *interoperability layer* includes definitions specific to a general product, process or resource as used across several disciplines (e.g. IfcDoor, IfcRamp, etc.); (4) The *domain layer* includes schemas containing entity definitions that are specializations of products, processes or resources specific to a certain domain (e.g. IfcHvacDomain, etc.).

2.2 Standard BIM Ontologies

When considering standard BIM ontologies, only one ontology exists namely the ifcOWL ontology. The process generating this ontology is described in [22]. The approach of [22] implements a conversion pattern (algorithm) provided in Java and C++ to convert the considered EXPRESS schema (simple, defined, list aggregation, array aggregation data types, etc.) into OWL (OWL class hierarchy, object properties, etc.). The generated ifcOWL ontology is in OWL2 DL, matches the original EXPRESS schema, and allows the conversion of IFC STEP files into equivalent RDF graphs. Different ifcOWL versions have been generated for each version of the IFC standard and are available online[1]. Several researches have tackled improving the standard ifcOWL ontology. [7] proposes an ifcOWL ontology where EXPRESS collections (e.g. LIST) are mapped as OWL properties, and IFC defined types are not directly converted to OWL classes. [7] proposes an IfcWoD ontology that has a lower expressivity ($\mathcal{ALUIF}(\mathcal{D})$ instead of $\mathcal{SHIQ}(\mathcal{D})$ for ifcOWL). IfcWoD comes with two main advantages compared to the standard ifcOWL version: (1) EXPRESS collections are mapped as OWL properties instead of RDF or OWL Lists, and (2) IFC defined types aren't directly converted into classes. This allows having shorter and more efficient SPARQL queries. [4] transforms the Construction Operations Building Information Exchange (COBie) standard into the COBieOWL ontology (in OWL Lite with an $\mathcal{ALCHIF}(\mathcal{D})$ expressivity) and apply Linked Data principles for linking it to vocabularies such as FOAF. The COBieOWL ontology is also aligned to the ifcOWL ontology by transforming the COBie MVD into SWRL rules [6]. Federation among the Ifc-

1 https://github.com/buildingSMART/ifcOWL

WoD and the COBieOWL ontologies is implemented using the FOWLA framework [5].

3 GIS and existing standard ontologies

3.1 Geographic Information Systems

As mentioned in the Introduction, GIS refers to "information systems dealing with information concerning phenomena associated with location relative to the Earth" [10]. ISO/TC 211 "Geographical Information" is the ISO technical committee in charge of standardization in the field of digital geographic information. Its goal is to "establish a structured set of standards for information concerning objects or phenomena that are directly or indirectly associated with a location relative to the Earth" [18]. GIS represents the information system that allows handling such objects and phenomena [10]. ISO/TC 211 has defined the different standards forming the ISO 19100 standard family. Conceptual modelling in the ISO 19100 series is based Model-driven Architectures (MDA). Four levels are considered: (1) Metamodel level contains “Geographic information — Rules for application schema.” (ISO 19109:2015) [12], and “Geographic information — Conceptual schema language” (ISO19103:2015) [19], (2) Conceptual (Abstract) Schemas level contains “Geographic information — Spatial schema.” (ISO 19107:2003) [11], “Geographic information — Referencing by coordinates.” (ISO 19111:2007) [13], etc., (3) Conceptual (Applications) Schemas level contains “Geographic information — Data product specifications.” (ISO 19131:2007) [15], “Geographic information — Imagery sensor models for geopositioning” (ISO 19130:2010) [14], etc., and (4) Implementation schemas level contains the actual data that is defined according to the standards present at the previous level.

3.2 Standard GIS Ontologies

ISO/TC 211 established a group for the maintenance of ontologies (GOM) responsible to create and publish ISO/TC 211 ontologies (https://github.com/ISO-TC211/GOM). The table below lists the standards that have associated ontology representations (as published on the TC211 website: https://def.isotc211.org/ontologies/). These ontologies are also published on the ISO/TC211 GitHub repository: https://github.-com/ISO-TC211/ontologies. Elements in bold in the table below are the standards concerned by the mappings defined in this paper.

Table 1. ISO 19100 standard family ontology representation

Metamodel level		
ISO standard	**Name**	**Description**
ISO 19101	Reference model	The ISO reference model dealing with geographic information, described from 4 viewpoints: semantic, syntactic, service, and procedural. One of the goals of this reference model is to "ensure interoperability" with other domains and to ease the integration of "integrate geographic information with other types of information and con-

		versely".
ISO 19103	Conceptual schema language	It provides rules and guidelines for the use of a conceptual schema language within the context of geographic information. The conceptual schema language used is the Unified Modeling Language (UML).
ISO 19109	**Rules for application schema**	The RulesForApplicationSchema imports UtilityClasses and GeneralfeatureModel ontologies from ISO 19109:2015, along with the base ontology from ISO 19150-2:2012.The GeneralFeatureModel ontology imports UtilityClasses ontology from ISO 19109:2015, NameTypes ontology from ISO 19103:2015, MetadataEntitySetInformation ontology from ISO 19115:2003 along with the base ontology from ISO 19150-2:2012.
Conceptual (Abstract) Schemas level		
ISO standard	**Name**	**Description**
ISO 19107	**Spatial schema**	The SpatialSchema ontology imports Geometry and Topology ontologies from ISO 19107:2003 along with the base ontology from ISO 19150-2:2012. The Topology ontology imports TopologicalComplex, TopologicalPrimitive, and TopologyRoot ontologies from ISO 19107:2003 along with the base ontology from ISO 19150-2:2012. The Geometry ontology imports CoordinateGeometry, GeometricAggregates, GeometricComplex, GeometricPrimitive, GeometryRoot ontologies from ISO 19107:2003 along with the base ontology from ISO 19150-2:2012
ISO 19108	Temporal schema	The TemporalSchema ontology imports TemporalObjects and TemporalReferenceSystem ontologies from ISO 19108:2006 along with the base ontology from ISO 19150-2:2012.
ISO 19110	Methodology for feature cataloguing	The MethodologyForFeatureCataloguing ontology imports FeatureCataloguing and FeatureCatalogueRegister ontologies from ISO 19110:2016 along with the base ontology from ISO 19150-2:2012.
ISO 19111	**Referencing by coordinates**	The ReferencingByCoordinates ontology imports CommonClasses, Coordinates, CoordinateReferenceSystems, CoordinateSystems, Datums and CoordinateOperations ontologies from ISO 19111:2019 along with the base ontology from ISO 19150-2:2012.
ISO 19112	Spatial referencing by geographic identifier	It establishes a general model for spatial referencing using geographic identifiers and defines the components of a spatial reference system. It only covers the definition and recording of the referencing feature, and does not consider the forms of the relationship.
ISO 19115	Metadata	It defines the schema required for describing geographic information and services. It provides information about the identification, the extent, the quality, the spatial and temporal schema, spatial reference, and distribution of digital geographic data.
ISO 19123	Schema for coverage geometry and functions	The Coverages ontology imports CoverageCore, DiscreteCoverages, ThiessenPolygon, QuadrilateralGrid, HexagonalGrid, TIN, and SegmentedCurve ontology from ISO 19123:2005 along with the base ontology from ISO 19150-2:2012.
ISO 19137	Core profile of the spatial schema	It defines a core profile of the spatial schema detailed in ISO 19107 that specifies, following ISO 19106, a minimal set of geometric elements necessary for the efficient creation of application schemata.
ISO 19141	Schema for moving features	It defines a method to describe the geometry of a feature that moves as a rigid body, such as feature that moves along a planned route, or motion influenced by physical forces.
ISO	Schema of	The standard provides ways to specify locations along linear elements

19148	linear referencing	such as transport network links or alignments. In essence, any object where a location can be referenced using one measure.
ISO 19157	Data quality	It establishes principles for reporting data quality, and also defines a set of data quality measures for use in evaluating and reporting data quality.
Conceptual (Application) Schemas level		
ISO standard	**Name**	**Description**
ISO 19104	Terminology	The Terminology ontology imports TermRegister ontology from ISO 19104 along with the base ontology from ISO 19150-2:2012.
ISO 19130	**Imagery sensor models for geopositioning**	The ImagerySensorModelsForGeopositioningPart1_Fundamentals ontology imports SensorData ontology from ISO 19130-1:2018 along with the base ontology from ISO 19150-2:2012.
ISO 19131	**Data product specifications**	The DataProductSpecification ontology imports DPS, SpecificationAdditionalInformation, SpecificationContentAndStructure, SpecificationDataCaputreInformation, SpecificationDataQualityRequirement, SpecificationDeliveryInformation, SpecificationIdentification, SpecificationMaintenanceInformation, SpecificationPortrayalInformation, SpecificationReferenceSystem, and SpecificationScopes ontolgies from ISO 19131:2007 along with the base ontology from ISO 19150-2:2012. The DPS ontotology imports SpecificationPortrayalInformation, SpecificationScopes, SpecificationDataCaptureInformation, SpecificationDeliveryInformation, SpecificationReferenceSystem, SpecificationDataQualityRequirement, SpecificationIdentification, SpecificationMaintenanceInformation, SpecificationContentAndStructure, SpecificationAdditionalInformation ontolgies from ISO 19131:2007 along with the base ontology from ISO 19150-2:2012.
Implementation Schemas level		
ISO standard	**Name**	**Description**
ISO 19116	Positioning services	It specifies the data structure and content of an interface that permits communication between position-providing device(s) and position-using device(s) to interpret position information and determine whether the resulting position information meets the requirements of the intended use.
ISO 19117	Portrayal	It provides an abstract model for developers of portrayal systems so that they can implement a system with the flexibility to portray geographic data to a user community in a manner that makes sense to that community.
ISO 19118	Encoding	It specifies the requirements for encoding rules, encoding services and XML-based encoding, for the interchange of data that conform to the geographic information in the set of International Standards known as the "ISO 19100 series".
ISO 19119	Services	The Services ontology imports ServiceMetadata, and ServiceModel ontologies from ISO 19119:2005 along with the base ontology from ISO 19150-2:2012.
ISO 19126	Feature concept dictionaries and registers	The FeatureConcepts ontology imports FeatureConceptDictionary, and HierarchicalFeatureInformationRegister ontologies from ISO 19126:2009 along with the base ontology from ISO 19150-2:2012.

ISO 19128	Web map server interface	The MapServices ontology imports ExtentInformation, and CitationAndResponsiblePartyInformation ontologies from ISO 19115:2006 along with the base ontology from ISO 19150-2:2012.
ISO 19129	Imagery, gridded and coverage data framework	The IGCD ontology imports IGCDFramework ontology from ISO 19129:2009 along with the base ontology from ISO 19150-2:2012.
ISO 19132	Location-based services - Reference model	It defines a reference model (e.g. enterprise, information, etc.) and a conceptual framework that contains ontology, taxonomies, etc. for location-based services (LBS), and describes the basic principles by which LBS applications may interoperate.
ISO 19133	Location-based services - Tracking and navigation	It describes the data types, and operations associated with those types, for the implementation of tracking and navigation services. It is designed to specify web services that can be made available to wireless devices through web-resident proxy applications, but is not restricted to that environment.
ISO 19134	Location-based services - Multimodal routing and navigation	It specifies the data types and their associated operations for the implementation of multimodal location-based services for routing and navigation.
ISO 19135	Procedures for item registration	It specifies procedures to be followed in establishing, maintaining and publishing registers of unique, unambiguous and permanent identifiers, and meanings that are assigned to items of geographic information.
ISO 19136	Geography Markup Language (GML)	It is developed within the Open Geospatial Consortium (OGC). GML is an XML schema for the description of application schemas as well as the transport and storage of geographic information.
ISO 19137	Core profile of the spatial schema	It defines a core profile of the spatial schema detailed in ISO 19107 that specifies, following ISO 19106, a minimal set of geometric elements necessary for the efficient creation of application schemata.
ISO 19139	Metadata - XML schema implementation	It provides the XML implementation schema for ISO 19115 specifying the metadata record format and may be used to describe, validate, and exchange geospatial metadata prepared in XML
ISO 19144	Classification systems	It is divided into two parts Classification system structure, and Land Cover Meta Language (LCML). The first part aims to develop future classification systems that offer more reliable collection methods. The second part allows different land cover classification systems to be described based on the physiognomic aspects.
ISO 19145	Registry of representations of geographic point location	It specifies the process for establishing, maintaining and publishing registers of representation of geographic point location in compliance with ISO 19135.
ISO 19146	Cross-domain vocabularies	It establishes a methodology for cross-mapping between vocabularies used by geospatial communities. Its purpose is to provide rules for ensuring consistency when implementing cross-mapping processes.

ISO 19150	Ontology	It defines rules and guidelines for the development of ontologies to support geographic information over the Semantic Web. It defines the conversion of the UML standards into OWL.
ISO 19154	Ubiquitous public access - Reference model	This standard considers Ubiquitous Public Access to geographic information. It defines requirements in terms of standardization of systems and services supporting it.
ISO 19156	Observations and measurements	Following the cooperation with OGC's Sensor Web Enablement (SWE) activity), this standard comprises 2 parts as derived from previously published OGC standards: Part 1 — Observation schema (OGC 07-022r1) and Part 2 – Sampling Features (OGC 07-002r3).
ISO 19159	Calibration and validation of remote sensing imagery sensors and data	It comprises 4 parts: Part 1 addresses optical sensors (published in 2014), Part 2 covers the domains of laser scanning e.g. LIDAR (published in 2016), while Part 3 addresses SAR/InSAR (published in 2018) and SONAR will be considered by Part 4 (to be published).
ISO 19160	Addressing	5 parts are considered for this standard, but only Part 1 Conceptual model has been published so far. It defines an address model along with definitions of concepts present in the model.

4 Related Work

Previous sections (2 and 3) introduced existing BIM and ISO/TC 211 ontologies. However, there is no previous studies that tackled or created any links between them. This section lists several approaches addressing semantic links among BIM and GIS application. Semantic Web Technologies link BIM and GIS domains through uni/bi-directional integration [21], [22] or unification e.g. ontology covering both domains [3]. However, the presented approaches focus only on building models and treat specific use cases. [2] worked on automatically generating CityGML LoD3 (City Geographic Markup Language is an open standardized data model and exchange format that stores digital 3D models of cities and landscapes. The extendible international standard for spatial data exchange is issued by the OGC and the ISO/TC211) building models from IFC using Semantic Web Technology by mapping different entities and properties (e.g. IfcRoof equivalent to RoofSurface). [3] semantically integrated IFC and CityGML by conceiving the UBM ontology (Unified Building Model). For this authors defined semantic relationships between IFC and CityGML schemas through transformation rules (e.g. IfcBuilding is equivalent to UBMBuilding and UBMBuilding is equivalent to _AbstractBuilding). [20] introduces BIM to GIS (B2G) mapping by applying perspective definition (B2G PD), element mapping (B2G EM) and LoD mapping (B2G LM) mechanisms. Where B2G PD concerns data extracting depending on the use case, B2G EM defines the object mapping mechanism in terms of BIM to GIS transformation of model elements. B2G LM concerns LoD definition and mapping from BIM to GIS model. [21] integrates BIM and GIS by applying the following steps: (1) ontology construction, (2) semantic integration through Graph Matching for Ontologies (GMO), and finally (3) query execution. In addition, IFC ontology is linked to other building ontologies, for example [24] presents mapping results between BOT (Building Topology Ontology) and other building ontologies such as IFC (e.g. bot:Site owl:equivalentClass ifc:IfcSite), SAREF4BLDG (SAREF Ontology for Building) (e.g. bot:Building owl:equivalentClass saref4bldg:Building), and BRICK (e.g. bot:Building owl:equivalentClass brick:Building). Following our analysis, we noticed the following limitations in existing approaches: (1) the mappings defined are mainly among IFC and a GIS application schema (CityGML, IndoorGML, etc.) and do not address GIS standard ontologies; (2) unification or integration approaches only link two ontologies (e.g. CityGML and IFC) and cannot be applied to link all existing BIM and GIS ontologies; (3) most mapping concentrate only on IfcProductExtension and the IFC concepts in the interoperability layer. Thus in the next section we'll examine and define several semantic links among concepts from ifcOWL and standard GIS ontologies. Our mapping concerns IFC4.1 (IFC4_ADD1 Ontology) which is the lasted IFC ontology published by buildingSMART and ISO/TC 211 ontologies [25-29] (ISO 19109:2015, ISO 19107:2003, ISO 19111:2019, ISO 19130:2018, ISO 19131:2017) published by GOM.

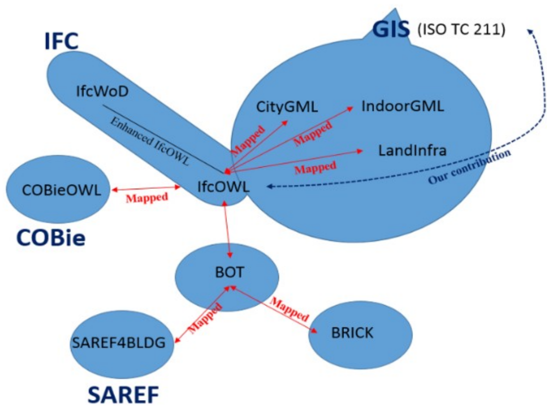

Figure 1: Previous mapping between BIM and GIS Ontologies

5 Ontology Mapping/ Alignment

As stated before we are aiming to map BIM/GIS through the definition of semantic links among standard ontologies namely those defined by ISO/TC 211 and IfcOWL 4.1. As described in [23], this contribution is part of a wider approach based on a two-axis federation e.g. vertical and horizontal federation. In our vision, horizontal federation focuses on creating semantic links between concepts and properties among both domains, while vertical federation specifies different abstractions of the same scope or context. Due to the limited number of pages, in this article we are only presenting mappings among a reduced number of ontologies from all those defined by ISO/ TC211. The links provided in the following paragraphs pertain to horizontal federation and are intended to: (1) link the GIS metamodel e.g. the General Feature Model (GFM) or ISO 19109:2015 and IFC concepts present in its core layer. (2) link GIS abstract conceptual schemas (e.g. ISO 19107:2003, ISO 19111:2007) and IFC concepts contained in the resource definition layer. (3) link GIS application schemas (e.g. ISO 19130:2010, ISO 19131:2007) and IFC concepts from the layers of domain specific and shared elements (ISO 16739-1:2018). In addition, note that the below standards correspond to the following name spaces:

- ISO19107 = "http://def.isotc211.org/iso19107/2003/SpatialSchema#"
- ISO19109 ="http://def.isotc211.org/iso19109/2015/ RulesForApplicationSchema #"
- ISO 19111= "http://def.isotc211.org/iso19111/2019/CoordinateReferenceSystems#"
- ISO 19130= "http://def.isotc211.org/iso19130/2018/SensorData#"
- ISO 19131= " http://def.isotc211.org/iso19131/2007/DPS#"
- IFC4.1 = "http://ifcowl.openbimstandards.org/IFC4_ADD1#"

5.1 Alignment between abstract schema and resource layer

In this section we are mapping GIS abstraction schema (ISO 19111:2007, ISO 19107:2003) and IFC resource definition layer.

Table 2. IFC4.1 and ISO 19111:2007 [13] concepts and properties

IFC resource layer	Description	ISO 19111	Description
IfcCoordi-nateRefer-enceSystem	It is a definition of a coordi-nate reference system using qualified identifiers only.	Coordi-nateSys-tem (CS)	It is the non-repeating se-quence of coordinate system axes that span a given coordi-nate space. A CS is derived from a set of mathematical rules for specifying how coor-dinates in each space are to be assigned to points.
IfcProjectCRS	It is a coordinate reference system of the map to which the map translation of the lo-cal engineering coordinate system of the construction or facility engineering project re-lates.	Project-edCRS	It is a derived coordinate ref-erence system which has a ge-odetic coordinate reference system as its base CRS and is converted using a map projec-tion.
IfcAxis2Place-ment 3D	Provides location and orienta-tions to place items in a three-dimensional space. The at-tribute Axis defines the Z di-rection, RefDirection the X di-rection, the Y direction is de-rived.	Coordi-nateSys temAxis	Defines coordinate system axis (axisAbbre, axeDirection, axe UnitID).

Table 3. Mapping IFC4_ADD1 and ISO 19111:2019 [27]

IFC4_ADD1.owl	Relation	ISO 19111.owl
IFC4.1:IfcProjectedCRS	owl:equivalentClass	ISO19111:ProjectedCRS
IFC4.1:IfcCoordinateRef-erenceSystem	owl:equivalentClass	ISO19111:CoordinateSystem

IFC4.1:refDirection_IfcAxis2Placement3D	owl:equivalentProperty	ISO1911:CoordinateSystemAxis.axisDirection

Table 4. IFC4.1 and ISO 19107:2003 [11] concepts and properties

IFC resource layer	Description	ISO 19107	Description
IfcEdge	Defines 2 vertices being connected topologically.	TP_Edge	Directed topological object that represents an association between an edge and one of its orientations
IfcBoundary Condition	It is the super type of all boundary conditions that can be applied to structural connection definitions, either directly for the connection (e.g. the joint) or for the relation between a structural member and the connection	GM_Boundary	The boundary operation for GM_Complex objects shall return a GM_ComplexBoundary, which is a collection of primitives and a GM_Complex of dimension 1 less than the original object
IfcEdge Curve	Defines 2 vertices being connected topologically including the geometric representation of the connection	GM_Curve	GM_Curve represent sections of curvilinear geometry, and therefore share a number of operation signatures.

Table 5. Mapping IFC4_ADD1 and ISO 19107:2003 [26]

IFC4_ADD1.owl	Relation	ISO 19107.owl
IFC4.1:EdgeCurve	owl:equivalentClass	ISO19107:GM_Curve
IFC4.1:Edge	owl:equivalentClass	ISO19107:TP_Edge
IFC4.1:IfcBoundaryCondition	owl:equivalentClass	ISO19107:GM_Boundary

5.2 Alignment between application schema and shared element layer

In this section we are mapping GIS application schema (ISO 19131:2007, ISO 19130:2010) and IFC shared element layer.

Table 6. IFC4.1 and ISO 19130:2010 [14] concepts and properties

IFC shared element layer schemas	Description	ISO 19130	Description
IfcTimeMeasure	It is the value of the duration of periods. Measured in seconds (s) or days (d) or other units of time.	dateTime	It is the time value of the taken measurement
IfcDimensionCount	It defines the dimensionality of the coordinate space. It is restricted to have the dimensionality of either 1, 2, or 3	numberofDimensions	Number of dimension

	for the purpose of this specification

Table 7. Mapping IFC4_ADD1 and ISO 19130:2018 [28]

IFC4_ADD1.owl	Relation	ISO 19130.owl
IFC4.1: IfcTimeMeasure	owl:equivalentProperty	ISO19130: SD_Dynamics. dateTime
IFC4.1: IfcDimensionCount	owl:equivalentProperty	ISO19130:SD_DetectorArray. numberOfDimensions

Table 8. IFC4.1 and ISO 19131:2007 [15] concepts and properties

IFC shared element layer schemas	Description	ISO 19131	Description
IfcApplication	It holds the information about an IFC compliant application developed by an application developer.	DPS_ ApplicationSchemas	It defines the conceptual schema for data required by one or more applications
IfcExtended-Properties	It is an abstract super type of all extensible property collections that are applicable to certain characterized entities.	Ex_Extent	It presents the description of spatial and temporal extent covered by data product

Table 9. Mapping IFC4_ADD1 and ISO 19131:2007 [29]

IFC4_ADD1.owl	Relation	ISO 19131.owl
IFC4.1:IfcApplication	owl:equivalentClass	ISO19131: DPS_Application-Schemas
IFC4.1:IfcExtendedProperties	owl:equivalentClass	ISO19131:Ex_Extent

5.3 Alignment between Metamodel and core layer

In this section we are mapping abstract GIS schema (ISO 19109:2015) and IFC core layer.

Table 10. IFC4.1 and ISO 19109:2015 [12] concepts and properties

IFC core layer	Description	ISO 19109	Description
IfcRoot	IfcRoot is the most abstract and root class for all entity definitions that roots in the kernel or in subsequent layers of the IFC specification. It is therefore the common super type of all IFC entities, beside those defined in an IFC resource schema	Any Feature	It represents the set of all classes which are feature types
IfcProduct Extension	Further specializes the concepts of a (physical) product, i.e. a component likely to have a shape and a placement within the project context	At-tribute Type	It recognizes all kinds of attributes: temporal, spatial geometry, spatial topology, data quality, generic meta-data, and location.

Table 11. Mapping IFC4_ADD1 and ISO 19109:2015 [25]

IFC4_ADD1.owl	Relation	ISO 19109.owl
IFC4.1:IfcRoot	owl:equivalentClass	ISO19109:AnyFeature
IFC4.1:IfcProductExtension	owl:equivalentClass	ISO19109:AttributeType

6 Conclusion and Future Work

The above mappings rely on concepts' and properties' definitions to instantiate equivalent relationships. However, those relations are not enough to achieve full semantic interoperability. In order to push our contribution further, we need to confront conceptual and semiotic heterogeneities which address differences in modelling, coverage and granularity representation between ontologies. We also need to implement structural ontology matching techniques that could enable a more robust mapping between BIM and GIS domains. Mapping BIM and GIS conceptual schema via ontologies will enable us to create data continuity between both domains, plug BIM model into any GIS application (e.g. CityGML, IndoorGML, LandInfra, etc.). Furthermore, the mapping is not limited to a specific use case and both domains must remain independent from each other because no meta-model is conceived or taken as reference. The mapping between BIM and GIS enables horizontal federation in our approach [23]. However, our approach also comprises vertical federation and for reaching it, the next elements must be considered: (1) Definition of mediator ontologies which establish terminological equivalences among schemas. (2) Definition of complex semantic mappings: which require exchanges with business experts. (3) Implementation of a granular approach: the concept of granularity, seems intuitive and easy to implement, still the associated abstraction levels and perspectives must be specified [23].

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