BIM4EEB

BIM based fast toolkit for Efficient rEnovation in Buildings

# D3.7 Harmonised common data exchange formats

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# D3.7 Harmonised common data exchange formats

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# EXECUTIVE SUMMARY

Collaboration in the AEC industry requires the exchange of building data between different software applications, systems and platforms. Building Information Modelling (BIM) sets out to address interoperability in building models and BIM where standards like the Industry Foundation Classes (IFC) aim to provide a reference model. IFC provides not only capabilities for storing multiple geometric representations but potentially describe parametric data, however the results are highly dependent on the way the data is interpreted by the tool. Moreover, as a result of the continuous specialization of tasks in the AEC industry, new domains are emerging which require a common representation to facilitate their exchange. Thus, there is a need to have a common and harmonised data exchange format to facilitate data sharing and data integration.

Although IFC is driven by the need to support data exchange across the entire building life cycle it has limitations to support relations, classification, properties, as well as geometric data. Moreover, IFC has not yet been aligned with widely used web technologies. As software applications are expanding their features and capabilities, requiring data from different sources and domains to perform their tasks more efficiently in order to satisfy the latest industry demands. The need to both exchanges the data from diverse data models and combine data from multiple domains makes it necessary to address the semantic and structural heterogeneity of the data where Semantic Web technologies and, in particular, ontology engineering, can carry out these tasks. Through ontology alignment it is possible to extract semantic relationships (mappings) between a data source and the target ontologies. The mappings between concepts are key to facilitating the transformation of data from one domain to another. Mapping-based transformations can also be performed to integrate data from different sources in order to represent them according to a target ontology. Furthermore, ifcOWL, and newer developments such as BOT, are opening up the capability to interlink and publish linked building data on the web.

Over the recent years, the semantic web technologies have been notably used in the architecture, engineering and construction (AEC) industry. One of the key motivations is to overcome the interoperability issue among existing and often used Building Information Modelling (BIM) software tools or at least improve information exchange processes, through the enhancement of existing, rich and well-known exchange formats. With this primary perspective, this document extensively analyses the related open standards and existing data models and exchange formats that have been used for sharing data among stakeholders. These analyses provide a guideline for standardization proposals of Technical Committee 442 of CEN as a robust stepping stone for getting a harmonised common exchange format with the application of semantic web technologies in the AEC domains.

# PUBLISHING SUMMARY

Communication between designers, builders, users and owners, transfer of data between domain-specific platforms and information storage and management together represent fundamental aspects of the complex topic of interoperability in the Architecture, Engineering and Construction (AEC) sector. The well-known Industry Foundation Classes (IFC) standard is the most important standard proposing a data model for the built environment, modelling both geometrical and non-geometrical information on a common format. Nonetheless, the expressivity of IFC is addressed as one of the causes for a limited application on the market. Recent research works, though, suggest the implementation of Semantic Web technologies, in particular the use of ontologies for knowledge representation, in order to overcome the linking and communication of data from different domains and sub-domains.

This document aims at harmonizing the results from previous Tasks of the same Work Package, by analysing the existing standardization framework and recent research efforts and, finally, highlighting possible features for a new data exchange standard to be presented at European level (CEN TC 442).

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# 1 Introduction

## 1.1 Scope of the document

In the last decades, CAD software solutions first, and BIM-oriented ones lately, have changed the development of projects in the Architecture, Engineering, Construction and Operation (AECO) sector, introducing many specific ways of representation of the built environment. Models created in this environment have information stored into different formats, and this creates issues of interoperability. For this reason, software houses creating tools and models for building representation have started developing common standardized formats aiming to enhance cooperation between operators and coherence of building models. Although, different disciplines like Building Energy Modelling (BEM), architectural modelling, structural analysis, cost estimation and analysis, etc., have different data requirements and formats for data exchange and their integration has different obstacles. The Industry Foundation Classes (IFC) standard is the main effort in this direction and it represents the most used common data format for information exchange. Besides its drawbacks, it represents the most efficient mean of data exchange, as it has been internationally recognized by ISO and consequently by the EU BIM Task Group in 2017 (EU BIM Task Group, 2017) as vendor-neutral, non-proprietary open file format.

Semantic modelling has been one of the main topics of research in the field of data exchange, mainly thanks to the enhanced possibility of querying and working over complex data sets. Various ontologies have been developed in the AECO sector to manage information in the domain and its sub-domains. In order to fully enable the expressivity of these technologies a standardized basic ontology for the domain has to be developed and integrated in the existing framework of standards and protocols for information exchange in BIM environment.

The scope of this document is to analyse commonly used information exchange formats and to integrate existing open-BIM data standards with new technologies and methods for interoperability and information exchange, besides pointing out critical issues of the existing framework. The deliverable has given a contribution to the definition of harmonised common data exchange formats, to be used in the context of BIM4EEB toolkit development, and the integration of open-BIM data standards for sharing information. Aiming for a full integration of these practices in the AECO sector and in particular renovation, features of the market, like the spread of these formats, the support on authoring software solutions, etc., are aspects considered in the analysis here proposed. Starting from these principles, this deliverable will deliver a comprehensive analysis of the existing standards and the preliminary stages of development of the BIM4EEB toolkit in order to (1) find information gaps in the standards or in the processes in which they are applied, and (2), finally, analyse and organize them in order to build a proposal to be discussed with other academics and professionals at national and community standardization bodies.

This document emphasis on the analysis of related open BIM standards and their history, that are applicable for defining a harmonised common data exchange format. Then an extensive analysis has been done on existing data exchange formats that are widely used for AEC industry such as IFC 4 and IFC 2x3, ifcXML, gbXML schema, etc. and Building linked data such as ifcOWL. Finally, the document proposes a synthesis of the analyses and consequent suggestions for the adoption of these efforts into standardization.

## 1.2 Relevance to other activities and state of the art

This deliverable reports about the work of Task 3.7, which aims at synthetizing the developments of the other tasks of Work Package 3 for standardization proposals. In order to do this, the task focused initially in analysing the existing framework of standards and protocols for building models and information exchange. In particular, outcomes of Tasks 3.2, 3.4 and 3.6 have been studied more in deep in this document.

The outcomes of this deliverable will be part of the discussion of open BIM standards at national and international level. These activities will be reported in D9.7.

## 1.3 Innovative results and progress

During Task 3.7 many theoretical and comparative analyses have been made aiming at defining the issues in developing a standardized format for information exchange and representation in the Semantic Web context.

This document is intended to provide guidelines for ongoing standardization efforts starting from the results obtained in the ontology framework development used for the toolkit application. The results of the analysis proposed in this document will be discussed by BIM4EEB representatives at various national and European level standardization level.

## 2 Methodology

According to the objectives of BIM4EEB, the project aims at analysing existing ontologies relevant to the renovation domain, proposing refinements and extensions and harmonising them. Further inter-model and inter-ontology relationships will be studied to integrate concepts which are currently absent or underdeveloped in current ontologies and that will be relevant according to the objectives of the proposal (e.g. comfort, occupancy, energy performance, workflow and process management, materials, equipment). In this context, task 3.7 focuses on the harmonisation of the results obtained in the previous WP3 subtasks to define suitable common data exchange formats that can be applied in the development of the BIM4EEB project components. To reach these objectives the D3.7 uses a structured approach as represented in the following figure.

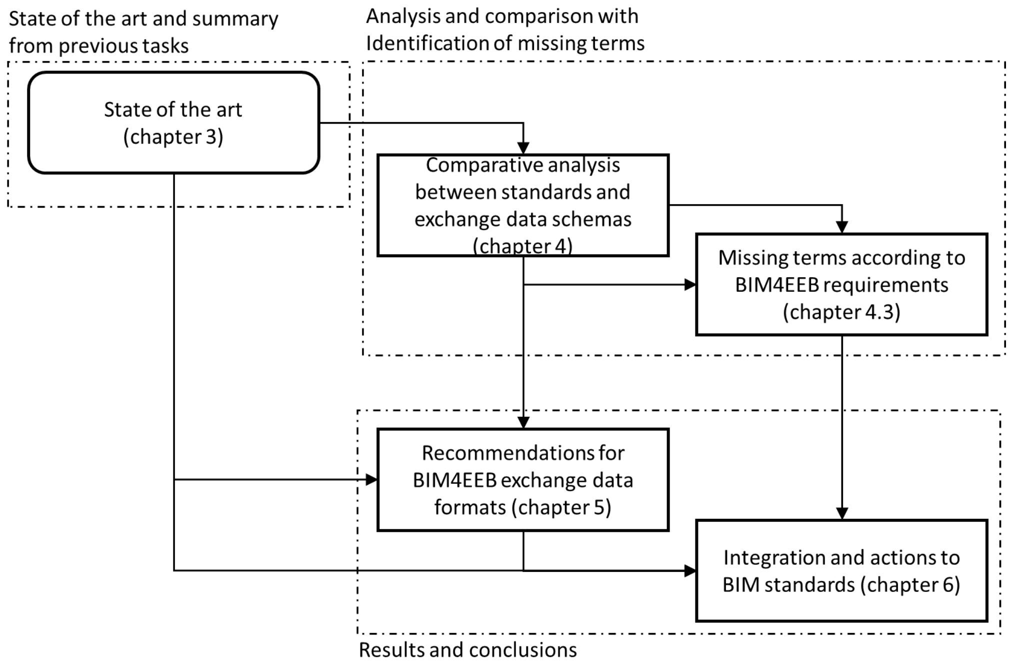


**Figure 1: Task methodology**

First, the deliverable collects the inputs received from previous subtask and synthesise the state of the art and the ontologies that have been analysed and defined in previous deliverables of work package 3. This state of the art is integrated with a comparative analysis that aims at identifying relations and discrepancies between the relevant standards and data exchange formats available in the construction context. Such analysis is also considered in the need of integrating the existing standards identifying missing terms according to the BIM4EEB requirements (i.e. according to renovation activities requirements).

The results of this analysis can then be used to provide two main outputs. On the one hand, the analysis of the state of the art and of the developed and existing ontologies. The comparative analysis and the identification of the missing terms allows to identify a set of recommendations that should be considered in the development of the BIM4EEB BIM management system and the related tools. Hence, the results of this work should be considered in addition to those under development in work package 4. On the other hand, the resulting table of missing terms and the issues that may be identified during the comparative analysis can be used as a basis to promote the improvement of existing standards, i.e. push the results to the relevant standardisation bodies.

# 3 State of the art

## 3.1 Open BIM Data Standards

In this section all the relevant standards in the field of open BIM data are listed. These standards regulate different aspects of the application of open BIM concepts for representation and information exchange. They range from classification standards to dictionaries and to data model. For each of these documents an overview has been given, considering the history of the development of the standards and their relation in order to harmonize the modelling of the built environment and the exchange of data.

### 3.1.1 Applicable Standards

***ISO 12006-2:2015 Building construction —Organization of information about construction works. Part 2: Framework for classification of information (International Organization for Standardization, 2015)***

This standard proposes to define basic and recommended classification table titles for building information management. It is intended to classify elements for both architecture and civil sector. In its update of 2015, examples of use of the concepts proposed are shown, helping the work of clarifying the purpose of an object-oriented model approach.

The standardisation of these classes started by analysing the existing and widely used classifications for cost analysis and specifications, referring in most cases to regional or national standards. Even though territorial and cultural differences are to be considered, it is fundamental to introduce a common framework for construction objects definitions, in order to ease the exchange processes and enhance international collaboration.

***ISO 12006-3:2007 Building construction —Organization of information about construction works. Part 3: Framework for Object oriented information (International Organization for Standardization, 2007)***

Part 3 of this standard gives the specification of a taxonomy model able to define not only objects, but also relations and groups, in EXPRESS language. Objects can have set of properties, numerical or non-numerical. The model has one root entity from which all the entities derive. The main subtypes of the root entity are *objects*, *collections* and *relationships*. The language independent model enables the exchange between information systems within a common framework. Once the role of an object is set, it is possible to define the context in which the object acts. The standard is written in the English language, but it is intended to model objects with multiple names, also with reference to other standard dictionaries. Objects are named with a “xtd” prefix, acronym for extensible taxonomy definition.

***ISO 10303 - Automation systems and integration — Product data representation and exchange (International Organization for Standardization, 2004)***

This standard, also known as EXPRESS, defines a language for data specification in its part 1. In part 11 specifies its graphical representation, called EXPRESS-G, allowing unambiguous data definition and specification of constraints inside a domain, besides the language reference manual. The standard is also known as Standard for the Exchange of Product model data (STEP) and it represents one of the largest efforts of ISO in delivering a product data exchange framework. The work for the specification has started in 1984 and covers a great variety of product types (electronic, mechanical, automotive, process plants, furniture, etc.) and life-cycle stages (design, planning, manufacturing, operating, etc.). It counts 549 active parts in 2018 editions, but the relevant ones for this Task are part 1, part 11 and part 225, which is an Application Protocol (AP). Many other parts are still under revision or under development. Active editions of standards part 1, part 11 and part 225 are from, respectively, 1994, 2004 and 1999.

Part 1 of the standard introduces the general structure and some basic definitions used throughout the other parts. It is organized in series of parts, published independently, with a numbering system dividing as it follows:

- Part 11: specifies the description methods;
- Part 21 and Part 22: specify the implementation methods;
- Part 31 and Part 32: specify the conformance testing methodology and framework;
- Part 41 to Part 49: specify the integrated generic resources;
- Part 101 to Part 105: specify the integrated application resources;
- Part 201 to Part 213: specify the application protocols;
- Part 301 to Part 332: specify the abstract test suites;
- 400 and 1000 series: specify the application modules (blocks to define modular APs).

The principles of product information exchange are highlighted in part 1, and in general the standard aims at providing machine-readable description of objects and processes for both file exchange and databases creation. The terms introduced in the first part are mainly related to generic terms like *data*, *data exchange*, *product*, etc. useful in the other parts.

Part 11 - *Description methods: The EXPRESS language reference manual* specifies the elements composing the EXPRESS language which form an extensible data model. Entities are defined according to their attributes, which may be a simple or complex data type. Relationships are defined, both between attributes and entities, and between entities. ISO highlights four design goals for the development of the language:

- The language should be easy to analyse from both humans and machines;
- The language should enable the division between the disciplines described as destination of the data model;
- Entities defined in the standard represent object of interest for the model and they are defined, as previously described, through attributes, always considering the domain context;
- The language should avoid adopting a particular implementation view, even though it allows the development of those.

Part 225 - *Building elements using explicit shape representation* is an application protocol (AP) for the exchange of information regarding building element shape and properties in the architecture, engineering and construction (AEC) field. It is intended to allow exchange and storage of building information from three-dimensional CAD drawings. This standard represents the first effort in creating a common representation format for geometrical building information. It aims to represent buildings without considering their mechanical or electrical subsystems, nor the information needed for energy or structural analysis. The model is built on the principle that a *building complex* is composed of *buildings* and a *site shape*; *buildings* are made of *building sections*, in turn composed of *building items*; each *building item* has a *shape* which may be *faceted* (lines and planes), *elementary* (lines, circles, ellipses, spheres, b-spline curves, etc.) or *advanced*.

***ISO 16739:2018 - Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries (International Organization for Standardization, 2018a)***

To facilitate data sharing in the construction and facility management industries, Industry Foundation Classes (IFC) has been introduced through ISO 16739:2013. This International Standard represents an open international standard for BIM data that is exchanged and shared among software applications used by the various participants in a building construction or facility management project.

This standard specifies a conceptual data schema defined in EXPRESS data specification language and an exchange file format for Building Information Model (BIM) data based on the conceptual schema using the Clear text encoding of the exchange structure. Other exchange file formats that are conformed to the specified conceptual schema can be used. This International Standard consists of the data schema, represented as an EXPRESS schema specification, and reference data, represented as definitions of property and quantity names and descriptions. The objective of this computer-interpretable representation is to provide a neutral mechanism capable of describing buildings and similar facilities in the built environment throughout their life cycle. This mechanism is suitable not only for neutral file exchange, but also as a basis for implementing and sharing product databases, and as a basis for archiving.

The data schema architecture of this International Standard defines four conceptual layers, where each individual schema is assigned to exactly one conceptual layer (BuildingSMART, 2020). Figure 1 shows the schema architecture.

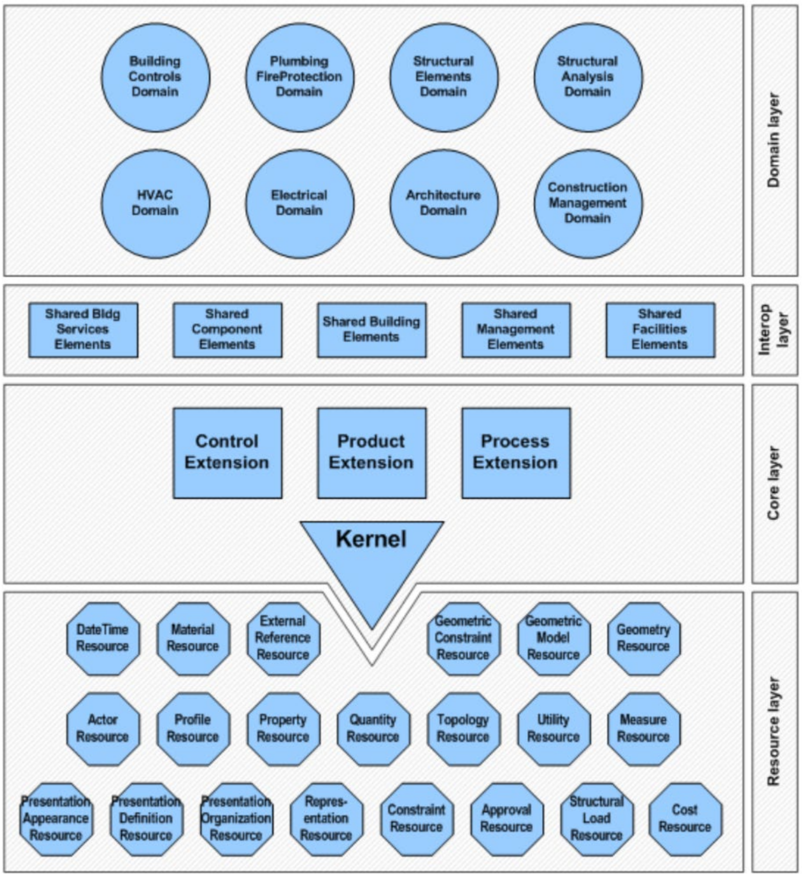


**Figure 2: Data Schema Architecture with conceptual layers (BuildingSMART, 2020)**

a. **Resource layer** — all individual schemas containing resource definitions are included in the lowest layer as shown in Figure 1. These definitions do not include a globally unique identifier and are used depending of a definition declared at a higher layer;**Core layer** — the kernel schema and the core extension schemas are included in the next layer, containing the most general entity definitions. All entities defined at the core layer, or above carry a globally unique id. Moreover, owner and history information are included optionally;

b. **Interoperability layer** — the schemas containing entity definitions that are specific to a general product, process or resource specialization used across several disciplines are included in the interoperability layer. Typically, those definitions are utilized for inter-domain exchange and sharing of construction information;

c. **Domain layer** — the schemas containing entity definitions that are specializations of products, processes or resources specific to a certain discipline are included in the highest layer. Typically those definitions are utilized for intra-domain exchange and sharing of information.

***ISO 6707:2017 Buildings and civil engineering works -- Vocabulary -- Part 1: General terms (International Organization for Standardization, 2017)***

Since 1984, this standard proposed a common dictionary for terms and concept of use in the construction industry. It provides definitions for both objects and works of relevance, in English, with all the possible different names according to their local use (mainly UK and US variants).

Similarly, to the first part of this standard, in part 2 the goal is to define a dictionary of communication and contract terms of importance in the industry.

***ISO/DIS 23386 Building information modelling and other digital processes used in construction — Methodology to describe, author and maintain properties in interconnected dictionaries (International Organization for Standardization, 2019b)***

The aim of this standard is to define a common set of properties for building dictionaries in order to ease the networking of the dictionaries themselves. Starting from the assumption that the complexity of the sector and the differences between the participants to the processes does not allow the easy creation of a unique dictionary, the work shifts towards the creation of networks between definitions of building elements and processes through the use of common parameters and standard attributes. These attributes are related also to the authors of the standards, easing the authoring process.

The standard provides definition of properties and group of properties, attributes for both properties and authoring individuals. Properties and group of properties are defined as lists of attributes in order to be machine and human readable at the same time. Attributes can be mandatory or optional. Every property can be included in different groups of properties, organised in different categories as it follows: class, domain, reference document, interdependent properties, specific use.

***ISO/DIS 23387 Building Information Modelling (BIM) — Data templates for construction objects used in the life cycle of any built asset — Concepts and principles (International Organization for Standardization, 2019c)***

To enable the construction project stakeholders to exchange information about construction objects through an asset life cycle, there is a need to provide a data template that uses the same data structure, terminology, and globally unique identifiers to enable machine-readability,
To fulfil this requirement International standard sets out the principles and structure for data templates for construction objects. It is developed to support digital processes using machine-readable formats using a standard data structure to exchange information about any type of construction object, e.g. product, system, assembly, space, building etc, used in the inception, brief, design, production, operation and demolition of facilities.

This standard provides the specification of a taxonomy model that defines concepts from EN ISO 12006-3, objects, collections, and relationships between them, to support the information need for the specific purpose of the data template. Moreover, this standard provides the rules for linking between data templates and IFC classes and rules for linking between data templates and classification systems within a data dictionary based on ISO EN 12006-3.

***ISO 29481:2016 Building Information Models Information Delivery Manual (International Organization for Standardization, 2016b)***

The Information Delivery Manual (IDM) is a standard aiming to define common principles to describe and display the needed information for every stage of designing, construction and management of a building or an infrastructure. The result of the organisation of information should be both human and machine readable, enabling automation of exchange and development of information.

***ISO 19650-1:2018 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM)***

ISO 19650 - *Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM). Information management using building information modelling* is a standard defining recommendations and principles for information management during the life cycle of a built asset. It is intended to guide the use of building information models (BIMs) in all the fields of application and for all the users of BIM. It is composed of five parts, but just part 1 and part 2 are active standards. The parts are divided as follows:

- Part 1: Concept and principles
- Part 2: Delivery phase of the assets
- Part 3: Operational phase of assets (under development)
- Part 4: Information exchange (under development)
- Part 5: Security-minded approach to information management (under development)

In Part 1 the workflow is described in four main steps: the work develops in the Work in progress phase; after an internal approval the work is shared between stakeholders; the work is revised; after this step, the work may be corrected or authorized; if authorized, the work is published.

Part 2 of the standard regulates appointing rules for actors of the process, aiming to provide a framework for efficient and effective information production. It applies to the delivery phase of the life cycle of an asset also known as the project information management (PIM) phase.

Part 3 considers the operational phase of the life cycle. In this last part, after project information are delivered, the information about the management of the assets and its occupants - so the asset information management (AIM) - become the focus of the standard.

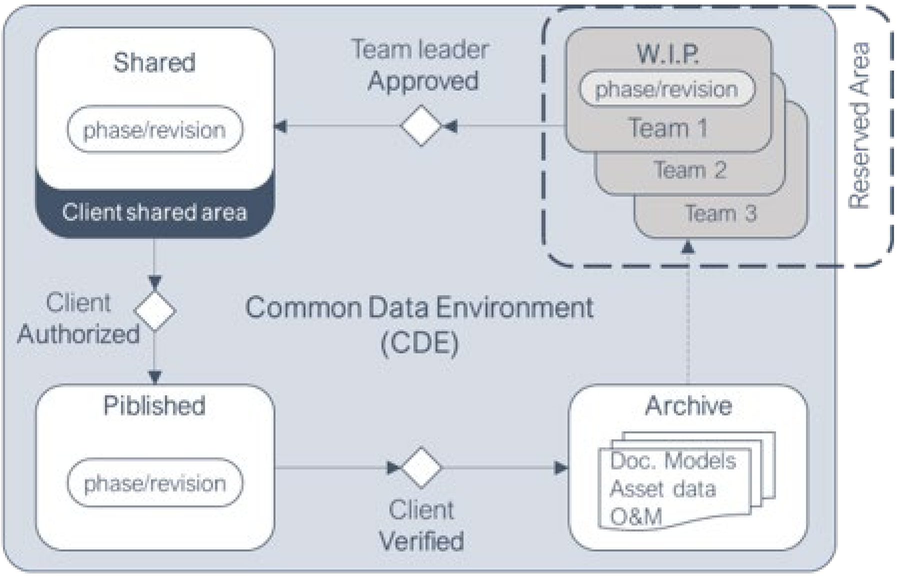


**Figure 3: CDE concept description in ISO 19650-1**

Part 4 of the standard defines the framework for information exchange inside a common data environment (CDE) for both the phases of PIM and AIM. This part of the standard also gives indications about criteria for revision and verification. Between these criteria there are conformity of the delivery format for models and documents, physical and spatial conflict, accuracy specifications and information containers management.

Part 5 deals with the growing risks of digital information use, providing suggestions about major vulnerabilities and about the control systems to be applied throughout the processes, referring to other security standards like ISO/IEC 27001. The spirit of the standard lies in the fact that security-oriented approached, based on the evaluation of risks, shall be applied across as well as within organizations of build environment actors.

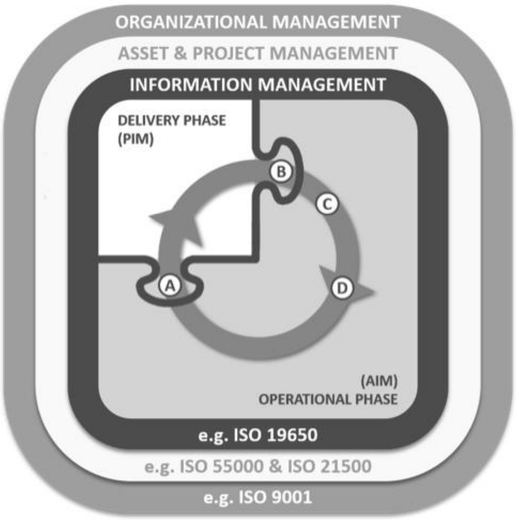


**Figure 4: Scope of ISO 19650-3**

***Other Standards***

ISO 15926 - Industrial automation systems and integration — Integration of life-cycle data for process plants including oil and gas production facilities (International Organization for Standardization, 2004) is the standard for the representation of process plant life-cycle information. It is composed of 13 parts (as July 2019) integrating the data model, reference data and implementation guidelines. It can be seen as an equivalent of ISO 16739 in the oil and gas and other facilities, with the advantage of including all the standards for dictionaries and implementation into one. This standard was developed with the aim of collecting and representing life-cycle data of industrial facilities. Many actors are involved in the design, construction, operation, maintenance and disposal of such structures, besides the fact that they require different professionals to be operated. All of these actors use different unstandardized software platforms even if they live in the same environment. In many applications the problem is identified in the implicit definitions of some information, which is understandable only by experts of the field. In this context, the aim of integrating into one format explicit definitions of objects of this particular domain assumes relevant importance to ease information exchange. Since Semantic Web technologies have proved to be effective in tackling these issues, regulators included in the same document specifications for the application in the field of Linked Data.

The standard contains 13 parts as listed below:

- Part 1: Overview and fundamental principles
- Part 2: Data model
- Part 3: Reference data for geometry and topology
- Part 4: Initial reference data
- Part 6: Methodology for the development and validation of reference data
- Part 7: Implementation methods for the integration of distributed systems: Template methodology
- Part 8: Implementations methods for the integration of distributed systems: Web Ontology Language (OWL) implementation
- Part 9: Façade implementation (
- Part 10: Conformance testing
- Part 11: Methodology for simplified industrial usage of reference data
- Part 12: Life-cycle integration ontology represented in Web Ontology Language (OWL)
- Part 13: Integrated asset planning life-cycle
- Part 14: Data model adapted for OWL2 Direct Semantics

All the cited standards are in status Published besides Part 10 and Part 14, while regulators are developing the second edition of Part 4. Part 9 was under development in 2014 updates, but it has been discarded by ISO in most recent publications.

The specifications for the data schema are described in Part 2 of the standard. It is designed to support activities and objects throughout the life-cycle of the facility. It is written according to the EXPRESS language standardized in ISO 10303-11. Every entity introduced in the data model includes a unique system identifier as a member of the EXPRESS string data type, even if entities can be coupled with external identifiers with a different attribute. The standard introduces entities, types, classes and basic relationships in form of axioms, layered in levels of abstraction identified by the entities *ClassOf* and *ClassOfClassOf*. The total number of entities introduced is 201. Objectified relationships regulate hierarchies between and general behaviour between entities like in any other data format in the same format. A particular mention has to be done for two relation entities called TemporalWholePart (as subtype of Relationship) and ClassOfTemporalWholePart (as subtype of ClassOfRelationship) because of their role in defining differences between generic enduring objects (physical objects, resources, etc.) and perduring objects (events, operations, etc.).

Part 4 introduces the initial reference data, which is the set of definitions describing objects introduced in the data model. Every concept has a unique identifier (URI), so that every object in the model is described just by the address of the definition in the dictionary. The standard also allows the use of a federation of data libraries, which may be useful in cases of international projects or different designers behind the development of a facility.

Part 8 discusses the implementation methods for an ontology representation in the Web Ontology Language (OWL). It proposes a translation of the data model in the RDF format, so with sentences expresses in triples. Sets of triples, so groups of sentences, can be extracted to represent the information needed from a specific point of view: this kind of storing and showing data is possible thanks to the stores, referred to as "façades". The part of the standard defining specifications for façades is still under development.

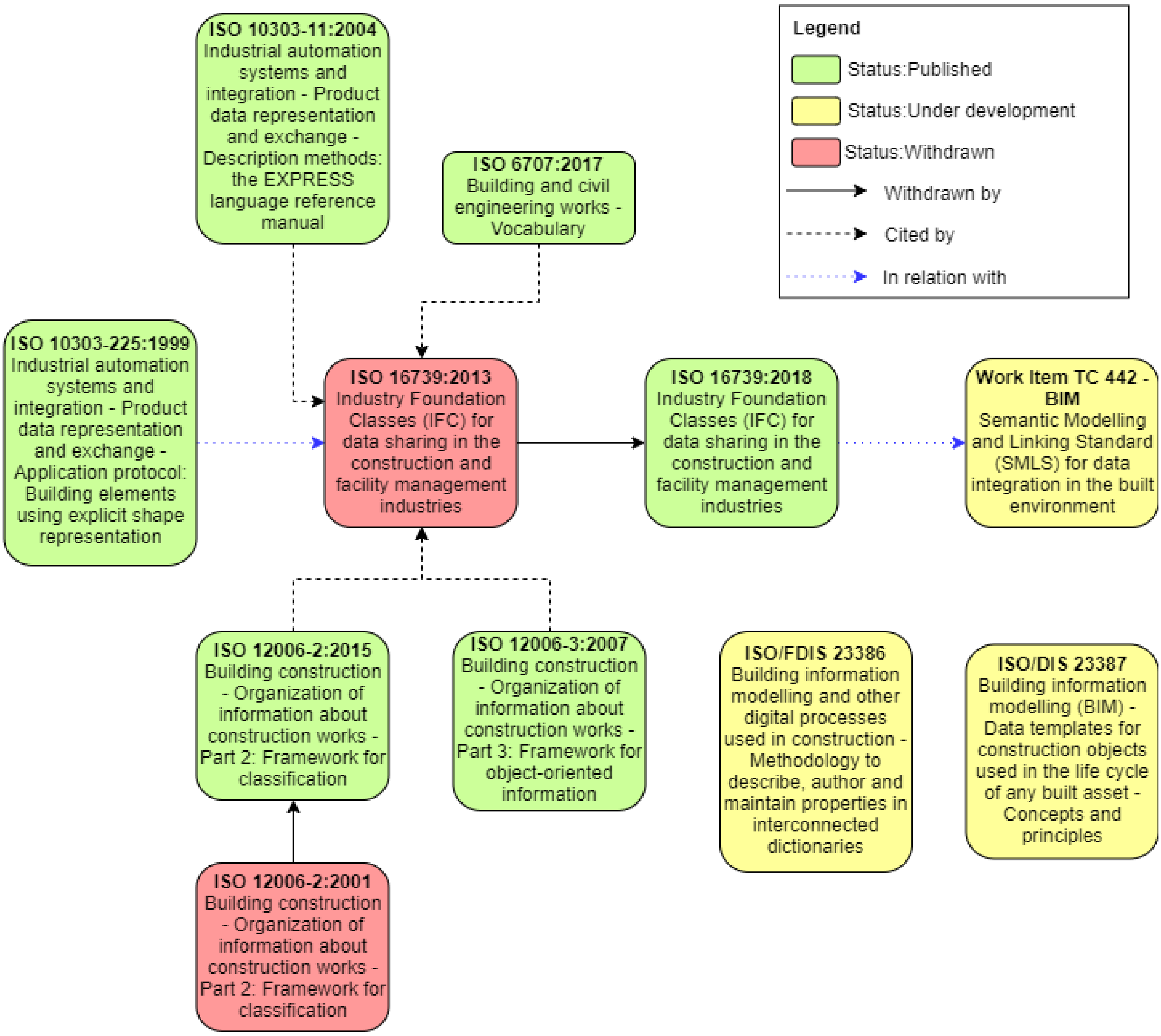


**Figure 5: Framework of standards analysed**

Figure 5 shows a synthesis of the standards analysed in this chapter. ISO 16739 plays a pivotal role as it defines a schema for data representation and exchange, according to definition given over different standards. The right part of the graph represents the future developments in the field of standardization, including the building Linked Data efforts still under development. The other standards were included because they are the main reference for the information exchange standard in the AEC sector. The analysis presented in the next section will highlight the importance of these standards in the context of BIM4EEB.
The relevant standards not included in the analysis of this tasks are listed below. These documents will be referenced by other tasks of the project, both for developing parts of the toolkit and for participating to the standardization processes.

ISO 21597:2020 - Information container for linked document delivery — Exchange specification is an international standard composed of two parts: part 1: Container and part 2: Link types.
This series of standard has been developed to represent information containers for the construction sector. Since information may come in different formats and, possibly, information can be based on ontologies, this standard aims at specifying relationships between heterogeneous documents inside a container. The standard is composed of two parts, describing respectively a generic container format and specification for extension of such types. Along with the container specification, the standard delivers links between data within those documents. The container is defined using semantic web standards like RDF, RDFS and OWL. The container defined in this standard is composed of a header and an optional link file, representing respectively the information about the container and its authors and the relation between documents. Part 2 of the standard starts from the links and increases the link types (e.g. aggregation, membership, replacement, etc.) for machine readability of these relations. The standards also highlights how the machine reasoning is not the focus, as other standards cover that field.

CEN TC 442- *Semantic modelling and Linking Standard (SMLS) for data integration in the built environment* is a standard (draft) that focuses on the (semantic) modelling and linking methodology of asset/project/product data. Thus, it provides the opportunity to implement software that can facilitate easy exchange of data and data sharing among involved parties in the asset's life cycle and supply chain. This standard recommends the use of RDF XML Syntax [RDF/XML] (file with extension .rdf), Turtle [Turtle] (file with extension .ttl) and JSON-LD [JSON-LD] (file with extension .jsonld), where the power of these formats are equivalent. RDF/XML is the formal normative RDF serialisation, Turtle is more convenient for human reading and interpretation, and JSON-LD for machine reading and interpretation like for semantic software development. Furthermore, this standard uses SPARQL as direct data access interface on RDF level for reading (SPARQL Select queries), writing (SPARQL Construct queries) and checking (SPARQL Ask queries). Beside these quite low-level technical languages this standard also defines a layered stack of subsets of modelling constructs provided by the W3C defined languages: XML Schema Part 2, RDF, SKOS, RDFS, OWL and SHACL, all having 'recommendation' status except for SHACL Advanced Features' partly dealing with 'rules'.

The main feature of this standard is the choice for the W3C Linked Data/Semantic Web (LD/SW) [LDSW] approach and technologies, that provides the basic formats, access methods and languages. This can be considered as the "conceptual modelling supply side" for fulfilling the demand side. As the data on the WWW is often unstructured and configured for human interpretation, Linked Data provides the structuring approach that makes the data 'machine processable' by software applications. Another layer of semantics can be defined on top, with ontologies containing concepts, datatypes, properties, relations and constraints & rules, giving powerful meaning to the data making it "machine-interpretable".

The default, simple approach for modelling of attributes and relations is by making direct use of the available language constructs provided by RDF, RDFS, OWL and SHACL. In OWL this means i.e. OWL data type properties for attributes and OWL object properties for relations.

## 3.2 Data Exchange Formats for Construction Industry

Since the introduction of digital documents in the architecture, engineering and construction (AEC) field, designers and operators have faced the problem of information exchange as professional use different applications available on the market with proprietary formats. The first step for standardization of industrial product data was made in 1984 by the International Organization for Standardization (ISO) with the development of ISO 10303, intended to cover purposes of manufacturing, transportation, energy facilities and building information. As building data live in a very complex knowledge domain and are produced throughout a long life-cycle time, spanning over decades, a very strong need of representing different kinds of data has risen. The following sub-section describes the most relevant efforts to produce data formats independent from authoring software solutions for sharing and collection of data.

### 3.2.1 Industry Foundation Classes (IFC)

Industry Foundation Classes (IFC) is an open data model introduced to ease the processes of collection and exchange of information in the architecture, engineering and construction (AEC) industry. It aims to define an object-based file format, made of objects and relationships organized according to a heritage hierarchy. It is written in EXPRESS language, as defined in ISO 10303-11.

The work towards a common file format started in 1994, when some software houses and other IT companies started a consortium, named the Industry Alliance for Interoperability, to build a set of classes to be used in the development of different integrated application, following the principles of Building Information Management (BIM). During the years the access to the alliance was opened to various companies and institutions, forming the international organisation known as BuildingSMART. Since 1995, several specifications have been released, starting from IFC 1.0 in 1996, IFC 2.0 in 1999, IFC 2x3 in 2006, IFC 4 in 2013, with updates up to 2016 with IFC 4 ADD 2, published as ISO standard in 2018 with version IFC 4 ADD 2 TC1.

The IFC model relies on five basic standards, namely Industry Foundation Classes (IFC from ISO 16739), International Framework for Dictionaries (IFD, from ISO 12006-2 and ISO 12006-3), Information Delivery Manual (IDM, from ISO 29481-1 and ISO 29481-2), Model View Definition (MVD) and BIM Collaboration Format (BCF). Although, IFC covers only the data exchange in the building processes, that introduces several issues of identification of information of different nature (e.g. geometrical and non-geometrical data, structural and energetic analysis results, technical documents, etc.). IFD is a framework, providing a taxonomy model for construction information, besides basic definitions. IDM is intended to regulate communication between the project participants, setting the rules for information exchange. The MVD contains the specific sets for the different model views required, according to the different needs. Finally, BCF is an open standard XML schema that facilitates the exchange of issue information through authoring tools.

Commonly used software in the industry, though, are not updated with newest releases of IFC, but they still rely on stable intermediate tools exploiting mainly IFC 2 releases. An important achievement would be to find flexible and fast methods to update tools for importing and exporting IFC files.

#### *3.2.1.1 Comparison on IFC 4 vs IFC 2x3*

With the aim to provide a central “conceptual data schema and an exchange file format for BIM data” The Industry Foundation Classes (IFC) standard as described in section 2.1.3 has been developed that is maintained by the BuildingSMART organisation. Using the IFC data model and instance serialisation formats, BIM data can be exchanged between heterogeneous software applications covering a wide range of use cases including 4D planning, 5D cost calculation and structural analysis.

The most commonly used IFC schemas are IFC2x3 - IFC2x3 TC1 (version 2.3.0.0 - 2.3.0.1) and IFC4 - IFC4 ADD2 TC1 (version 4.0.0.0 - 4.0.2.1)[1]. As IFC 2x3 has been used for more than ten years in the industry, numerous sample IFC 2×3 implementations in widely adopted software tools are available and in use in practice. Thus, real-world sample files are available. IFC4 is the last available version of IFC. It has got the traction among the stakeholders in the industry. IFC4 ADD2 TC1 is the most updated version published in ISO, with the name of ISO 16739-1:2018. Latest version of IFC are used by the major BIM-oriented tools.

With every new release of the IFC schema BuildingSMART releases a changelog, explaining both the rework on the existing elements and the new items introduced. It aims to include suggestions from users and developers, to build consistency and coherence over the updates and to reduce the weight and the footprint of the model itself.

The active standard version has been deeply analysed for two main reasons: at first, to compare the technical differences between IFC 2x3 and IFC 4 schemas, but also to clearly understand the reasons and the nature of the active standard open BIM schema. The most important changes between the two considered versions are here listed by category.

- Core definitions
    - All types and objects, including their property sets can be associated to a project;
    - Product types can be decomposed into parts (e.g. structural type objects and their relative cut-outs, openings etc. are introduced);
    - Property set templates and property templates are introduced inside project data set
- Building elements and materials
    - More complex material definition for linear objects like columns and beams. These elements now include axis representation and allow complex profile shapes. Material definition is improved thanks to the possibility to define material profile sets (as it is for wall and slabs with material layer sets) with priority tags for joint representation. Composite materials are now easier to be defined;
    - Materials now support description and category fields for the use of generic classification systems;
    - Distribution systems and circuits are now represented with new entities;
    - Environmental impact property sets have been introduced;
- Spatial elements
    - A new entity (IfcSpatialElement) is introduced to generically represent spaces in the building context with their location, shape and functional type;
    - Zones can be assigned to different layers and stories;
    - External spaces separators are introduced, allowing for calculation end definition of different values like gross volume of stories or buildings, etc.;
    - The Cartesian coordinate system now includes projection information for projection in map coordinate systems;
    - New entities are introduced to represent geographic elements on site;
- Processes and cost
    - The concept of process type has been introduced, together with process subtypes. Also, the sequencing of processes is applicable both to types and occurrences. The task times and sequencing are no more defined with a relation to a schedule, but as a new entity within the task (IfcTaskTime). Same principles are applied to cost entities, in relation to quantities and not time;

[1] https://technical.buildingsmart.org/standards/ifc/ifc-schema-specifications/

- HVAC and other systems elements
    - Spatial elements introduced in the new version are useful also for energetic zone definition;
    - HVAC entities have been semantically improved and classified according to different parameters, like their behaviour or function. As an example, electric heaters are no more classified as electrical appliances but as space heaters, or audio/video devices have been separated from electrical appliances;
    - Linear elements such as pipes and ducts have been improved with axial representation and further improvements for parametric design, with the same principles of other linear elements (beams, columns, etc.);
    - Electrical protection devices have been detailed with more properties' specifications;
- Classification
    - The most used spatial and building elements now support multi-lingual definitions in Chinese, German, French and Japanese;
    - Materials are defined with description and category for classification use, also considering different classification systems;
    - Entities within the Resource Layer of IFC architecture now support identifiers defined through the use of external reference location and reference attributes. Within these attributes, classification and library references support a URI (Uniform Resource Identifier) reference;
    - Classification references can be assigned to properties;
    - Labels for classification or library references are enriched: they can have facets or language attributes.

Other improvements can be found in the IFC 4 ADD2 TC1 documentation, including a complete list of introduction and changes to individual entities, properties or property sets.

The updates to the IFC schema highlight some of its weak points and the strategies applied to solve these issues. Many efforts throughout the synthesis here proposed focus on the semantic base of entities. The strategy highlighted in the Core definitions part is identified by the enlargement in the use of enumeration types. The IFC object catalogue, considering inheritances and relations through definitions, can be used to map external classification. URI references and multi-lingual dictionaries also suggest the direction of the improvements to this version of IFC.

It is also important to mention the improvements in the definition of spatial elements. The introduction of *IfcSpatialElement* as generalization of all spatial elements of a project leads to the improvement of communication between different domain specific models. Considering topological elements, the introduction of entities representing geographic elements or the projection of the Cartesian coordinate system into a map coordinate system, both allowing a bridge to GIS data. From the Classification point of view, the introduction of URIs for classification and library references opens to the use of external defined identifiers with reference attributes.
Considering MVDs (Model View Definitions), IFC 4 introduces new Model View Definitions to make them more specific to the intended purposes. As a matter of fact, IFC 4 introduces the Reference View, for viewing and coordination purposes, and the Design Transfer View, specifically designed for high fidelity exchange between software solutions for design and evaluation tasks. Other MVDs are under development and they are the Quantity Takeoff View, for estimation and resource management purposes; Energy Analysis View, for cost and consumption measurement; Product Library View, for manufacturer product information sharing; and the Construction Operations Building Information Exchange 2.4 (COBie 2.4) view, for lifecycle information about management and operation of building systems.

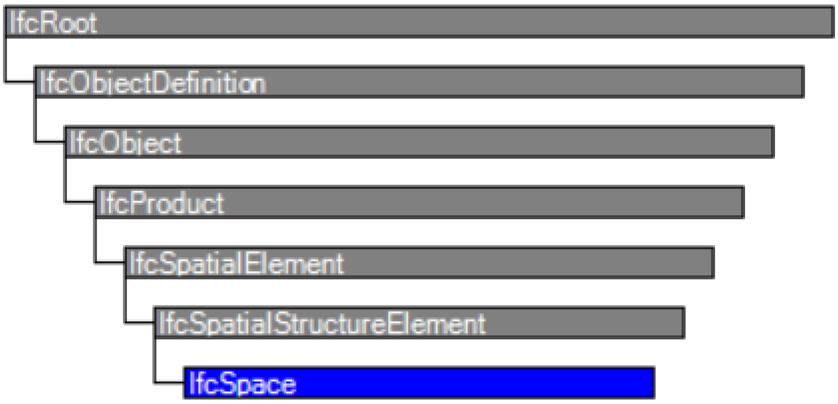


**Figure 6: IFC 4 inheritance tree for IfcSpace (BuildingSMART, 2020)**

The greatest achievement of the update of MVD in IFC 4, as stated by BuildingSMART is the support for mvdXML, which ease the process of software certification on one side by making the MVD machine-readable, and consequently improving the spread of standard MVD in the construction market through new technologies of automated checking tools.

### 3.2.2 Data Models and Exchange formats for Linked Building Data

Since the introduction of Building Information Models, the need for an exchange of information has risen. Web of Data technologies, together with BIM principles represent one of the most interesting trends of research to enhance information exchange processes. Among the challenges of creating frameworks for building linked data there is a wide variety of type of data (geometrical, sensor data, GIS data and so forth), of users (designers, owners and building users) and authoring software solutions working with different languages and different data schemas.

Semantic Web, introduced as a research topic in the early 2000s, is addressed as the technology that, thanks to the concepts of machine readability, can ease information exchange and automation in construction. With HTML, as an example, it is possible to categorize the content of web pages, describing pages and links between them, while with Semantic Web tools allow the description of objects and systems on a machine-readable basis, enhancing automated recognition and other operations.

Semantic Web is enabled through different tools, standardised by W3C, and the main ones can be highlighted as the Resource Description Framework (RDF) and Web Ontology Language (OWL). RDF is a data scheme expressed in the form of *subject-predicate-object*. The statements written in this form are known as triples. This schema can easily create statements between resources available on the internet, through URIs.

The application of Semantic Web in particular domains has brought to OWL, presented in 2002 as a family of languages of knowledge representation through ontologies. Starting from axioms in the specific domain, ontologies can define the type of objects (classes) through basic statements and the properties definitions. The web environment in which ontologies are stored allows the ease of the relationship between individuals for both humans and machines, allowing processes like machine learning. In writing RDF statements, it is important, though, to agree on the semantics of resource identifiers.

#### *3.2.2.1 IFC based exchange formats: ifcOWL and ifcXML*

In the building sector researchers are studying possible ways of application of Semantic Web Principles to the existing data schemas representing the built environment. Linked Data Working Group started this work by developing the ifcOWL ontology starting from the IFC standard and building an IFC-to-RDF converter, to recreate the IFC EXPRESS schema into an RDF one. The pure conversion of IFC schema into ifcOWL early resulted in a complex data structure difficult to handle. The main issues to solve are the representation of geometrical data and complexity issues given by the IFC schema, in particular the grouping relationships between individual elements. In chapter 4.2 an analysis about reasons and methods of conversion of the IFC schema to an ontology is presented.

Differently from ifcOWL, an XML representation of IFC data was proposed in 2004 to spread the data model through other platforms and to ease the creation of web services on a supported and widely tested framework. Nonetheless, the same issues affecting ifcOWL about complexity of models are true also for ifcXML. Adding to this, the XML schema loses some rules, inverse relationship or attribute considering the EXPRESS schema.

Together with these efforts, BuildingSMART Data Dictionary[2] (bSDD) has been developed as a mapping tool based on the ISO 12006-3 ontology. This project started in 2014 aiming to connect IFC parameters to user databases in a language independent environment. It is based on a Google infrastructure and it is composed of an Open Exchange Layer, a Common Object Platform with its set of rules and tools (Host context, Property Set Management Tool, Quality testing and Open Multilingual Connectivity).

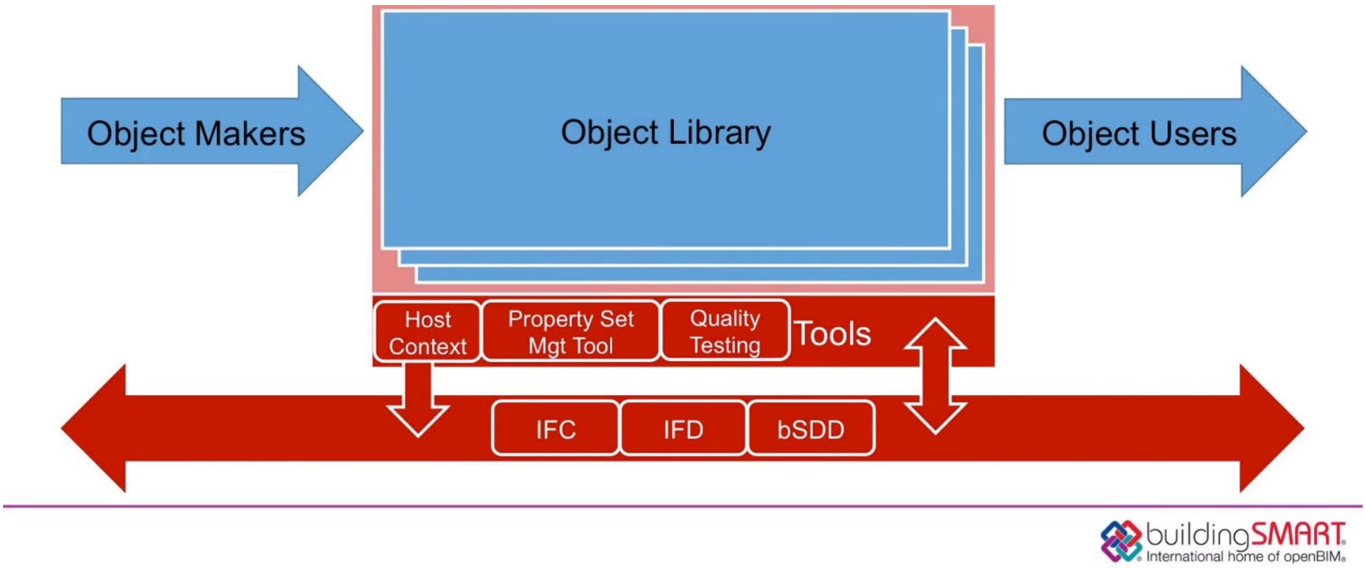


**Figure 7: bSDD common object platform[2]**

bSDD is intended to ease the definition of objects and parameters in libraries, helping their translation and sharing. bSDD, in relation with IFC, can be exploited to extend the data schema with new objects, properties and property sets, always considering the constraints of the existing standardized schema. The platform allows registered users to access and add contents, without acting directly on the IFC entities, on the other hand, tools and workflows are being developed to allow the use of extended IFC data defined in bSDD.

#### *3.2.2.2 Building Topology Ontology (BOT) and related tentative standards (W3C)*

Building Topology Ontology[3] (BOT) is a basic ontology representing the core topological concepts of a building in its context. It aims to be a baseline for the extension in various domains, from Building Management Systems (BMS) to Smart City technologies, following the principles of W3C of keeping he schema as simple as possible. It responds to basic principles of relationship between definitions of zones,

[2] http://bSDD.buildingsmart.org/
[3] https://w3c-lbd-cg.github.io/bot/

spaces and volumes. The basic principles, written in the ontology in the form of axioms in triplets, can be summarized in seven points:

1. Zones are areas with spatial 3D volumes, and include Buildings, Storeys, and Spaces.
2. Zones may contain other zones, Buildings may contain storeys, Storeys may contain spaces.
3. Zones may intersect or be adjacent to other zones.
4. There are building elements, which may have sub elements.
5. Zones may have elements, either contained, adjacent, or intersecting it.
6. Adjacent zones and/or elements share some interface.
7. Zones and Elements have a 3D Model (including geometry, material, etc.).

It is organised starting from the definitions of zone, site, building and space, then in between spaces interfaces are defined. Several alignment modules have been designed, as dictionaries to translate the ontologies into different schemas, including ifcOWL.

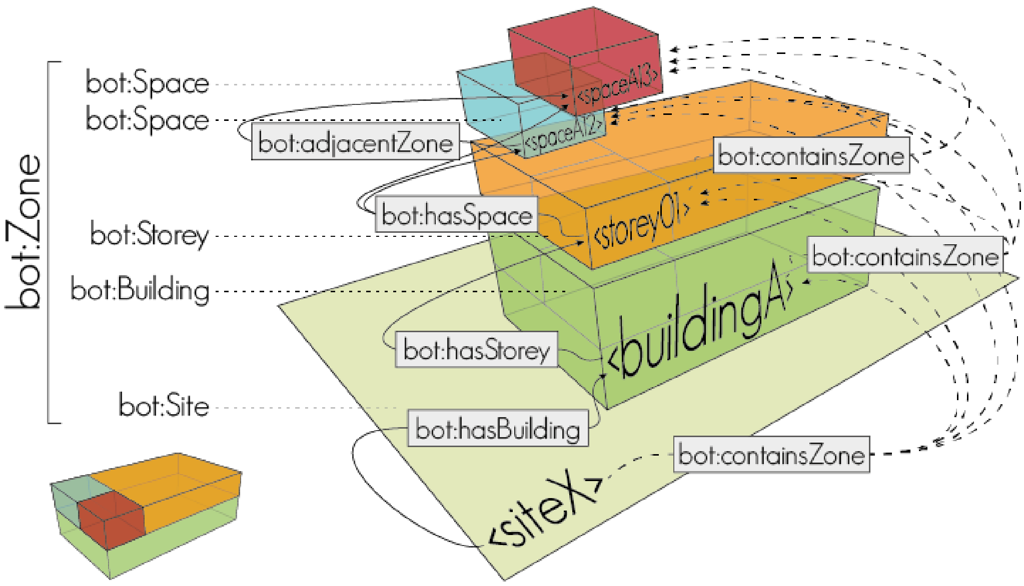


**Figure 8: Basic spatial entities and relationships of BOT**

BOT supports the alignment to various other ontologies such as ifcOWL, Brick, DogOnt, DERIROOMS, through specific modules.

### *3.2.2.3 Other initiatives*

Many other groups of researchers have been developing ontologies in sub-domains of the construction sector. The principles of Semantic Web applications allow the connection of different domain specific ontologies sharing the same semantic base, in a modular way.

#### 3.2.2.3.1 RealEstateCore

RealEstateCore[4] is an ontology built on using existing standards, with appropriate annotations, oriented to the control of assets and the management of buildings in the context of smart cities. It bridges different domains, such as the digital representation of buildings, the management of buildings in terms of

[4] https://doc.realestatecore.io/2.3/core/index-en.html

operations and IoT technologies. The defined concept of *RealEstate* is intended for building owners, and it represents the root entity of the data model. As sub-classes of this root entity, the site and buildings in its elements and spaces are defined. It consists of 37 Classes, 22 Object properties, 40 Data Properties, 12 Annotation Properties and 137 Named Individuals.

#### 3.2.2.3.2 Brick ontology

Brick ontology[5] is an open source data model created with the purpose of representing metadata in complex buildings, with particular focus to commercial buildings. It was developed by BuildSys, an international organization of researchers and practitioners working on computer and sensor technologies for the energy efficiency of buildings in smart cities context. The workflow in developing the ontology works as it follows: first, 333 entities were defined, then the relationships between were highlighted and written on form of triples; finally, the list was converted in Turtle format.

#### 3.2.2.3.3 BMS ontologies: SAREF, DogOnt and Rooms

In the particular domain of Building Management Systems there are many attempts of creation of ontologies managing data from different kind of sensors, able to be included in building data models.

Smart Appliances REFerence (SAREF)[6] ontology, starting from basic definitions of devices and services related, in a network environment, defines the semantic assets of a large variety of home and office appliances. The block schema of the ontology allows separation and recombination of the ontology depending on specific needs. Final version of this ontology was released in 2015 and it includes ontologies from various semantic assets, i.e. different data exchange protocols and data schema in the IoT devices domain. A total of 21 ontologies were developed in the project.

DogOnt[7] was firstly developed in 2008 to represent home automation devices, but at the state of the art it has become more flexible and modular according to the principles of Internet of Things (IoT). The interaction of devices towards the built context around them is one of the major focus of the work. It focuses on device modelling and device capabilities inside the built environment. It mainly describes:

- Where a (smart) device is located;
- The set of capabilities of a device;
- The technology-specific features needed to interface the device;
- The possible configurations that the device can assume (states);
- How the smart environment is composed;
- What kind of architectural elements and furniture are placed within?

All the cited ontologies are recognised by the Linked Data Working Community and are interconnected with the well-known ontologies previously described.

### 3.2.3 Green Building XML Schema

The term Green Building XML (cf. (Karlapudi, 2018)) usually referred as gbXML. This schema saves the data in terms of XML (eXtensible Markup Language) language which is both machine readable and human readable language. The Green Building XML schema, or gbXML, was developed to "facilitate the transfer of building information stored in CAD-based building information models, enabling interoperability between disparate building design and engineering analysis software tools. This is all in the name of helping

[5] https://brickschema.org/ontology
[6] https://ontology.tno.nl/saref/
[7] http://iot-ontologies.github.io/dogont/documentation/index-en.html

architects, engineers, and energy modellers to design more energy efficient buildings” (Bell, 2014).

The fundamental structure of the gbXML schema is shown in Figure 9 and it represents the hierarchy of the gbXML schema, which consists of Location, Building, Space, Surface, and Opening. gbXML imports the object-based elements (Walls, Roof, Floor, etc.) from the BIM tool as a virtual element with 2D surfaces. This is the reason for defining Walls, Floors, Roofs and Ceilings as a surface element in the gbXML structure.

The position of surface elements is represented based on two parent nodes. They are as follows.

- Space Boundary Node: which defines the centreline of the surface
- Shell Geometry Node: which defines the inner surface of the wall, etc.

Twice the difference between Space Boundary node and Shell Geometry node gives the thickness of the element. In the gbXML structure, Room and Shading Surfaces belong to the Building Space (refer in Figure 8). In Revit Architecture the user defines ROOMS and in Revit MEP (Mechanical, Electrical, and Plumbing) the user defines SPACES. The export process can be carried out based on either ROOM or SPACE. Rooms are defined by bound volumes. Spaces are defined by room bounding elements. The room bounding elements are Walls (Curtain, Standard), Roofs, Floors, Ceilings, Curtain System and Room Separation Lines. In all the cases, surfaces which do not belong to room bounding are treated as shading elements (Bell, 2014).

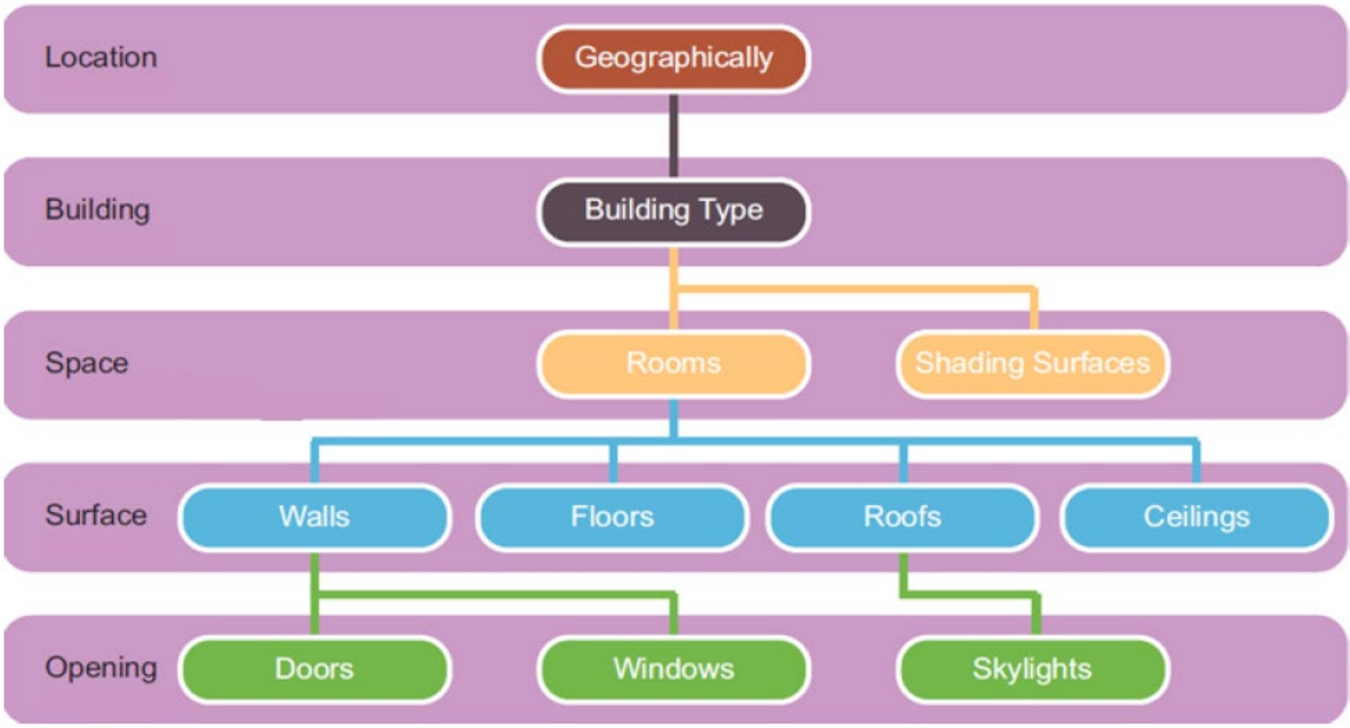


**Figure 9: gbXML structure (Bell, 2014).**

#### *3.2.3.1 Information organized in the gbXML schema*

gbXML is a meta-data schema for the data interoperability between different software tools in the AEC industry. This meta-data model is highly data enrich and capable of describing 500 types of the building elements and attributes. The below Figure 9 shows the hierarchical structure of the gbXML schema and explains the organization and management of the information in the schema.

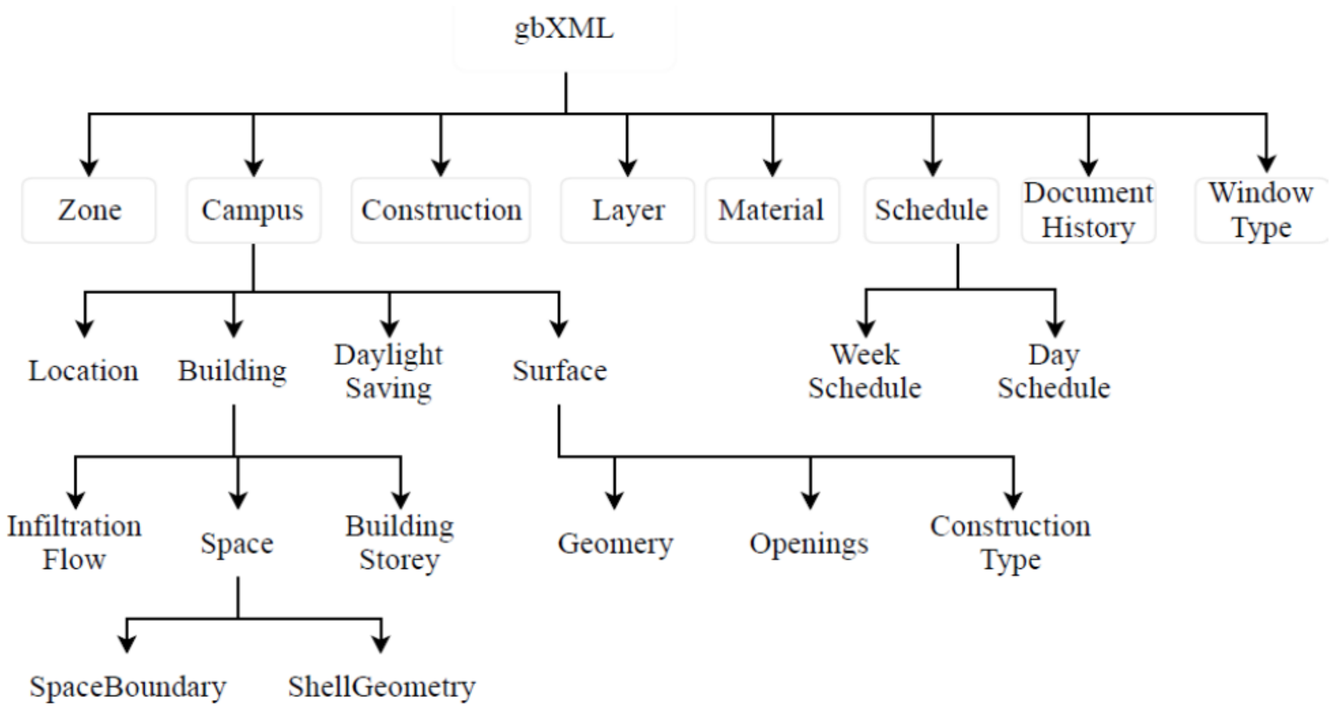


**Figure 10: Hierarchy of the information organized in the gbXML Schema (Karlapudi, 2018)**

There are different components defined in the gbXML library to hold the information from respective architectural or MEP models. Table 1 below represents components and explains their characteristics and the type of information carried by each component. Here, each component is defined by its own Reference Id. The main concept of this Reference Id is to create an Identification for each component in the schema and to define the relationships between components based on Reference Id.

In a gbXML schema all building elements like a wall, floor, roof, ceiling, etc. are defined as a surface. The surface component defines the geometry and construction for the building element. It also contains the information regarding openings in the element. The detailed description about construction like layers in the element, material and thermal properties of each layer are defined separately and related to construction type in the surface component based on the Reference Id relationship. Similarly, the details about the type of window or door types are related to the opening using Reference Id relationships.

The “Building” component in gbXML (refer to Table 1) defines different levels in the building (Building Storey) and space type details in each level of the building. Space is defined by the room bounding elements (surfaces: wall, floor, roof, etc.). The bounding element of space is defined by two nodes such as Shell Geometry and Space Boundary. Shell Geometry defines the coordinates of the inner surface (towards space) and the Space Boundary defines the Co-ordinates of the centreline of the bounding element. It means the difference between these two node points is equal to the half of the thickness of the element. But, in the case of the internal wall or the space separating element, the centreline and both sides of the wall are defined because this internal wall is bounded by a space on its both sides. The operating schedules of spaces and the occupant’s schedules are defined separately and link to the spaces based on reference ID.

**Table 1: Information organized in the gbXML schema (Karlapudi, 2018)**

| **Component** | **Characteristics** | **Information carries** |
|---|---|---|
| *gbXML* | XML schema represents the Building data | Units Type (SI or imperial), Unit for temperature, length, area, volume and version |
| *Campus* | A group of buildings that are geo-graphically similar | Id, Location, Building, Sur-face, and Daylight savings |
| *Location* | Location details of a building | Longitude, Latitude, Elevation, and Location name |
| *Building* | One building data | Building type, area, name, Id, street address, Description, Building Storey, infiltration and its Spaces |
| *Infiltration flow* | Airflow into the building due to unwanted leakages | Describes Tight, loose and medium infiltration flow |
| *Space* | A room defined by its own set of Walls, Ceiling, and/or roof. Space may be an office, conference room, warehouse, or any other entity | Space Id, Reference building Storey Id, Reference zone ID, space type, Reference light schedule Id, Reference equipment schedule Id, condition type, Reference occupants schedule Id, Area and Volume of the space, name, description, Geometrical coordinates (shell geometry, space boundary), number of people, people heat gain (La-tent & Sensible), light power per area |
| *ShellGeometry* | Defines the coordinates for the internal surface of walls (in terms of boundaries of a space) | Id, Cartesian Point, PolyLoop (set of Cartesian points which defines the geometry) |
| *SpaceBoundary* | Defines centreline of a space bounding element and its relationship with the adjacent space. | Id, isSecondLevelBoundary, PolyLoop, etc. |
| *Building Storey* | Describes different levels (storey) of building | Id, Level, Name |
| *Surface* | A wall, floor, ceiling, roof. Each space (or room) will have its own set of surfaces | Surface Type, exposed to the sun, Id, Adjacent space ID, Reference construction ID, name, details about construction type, geometry and openings |

| | | |
|---|---|---|
| *Geometry* | Shape and position of surface, space and openings | Id, azimuth, Cartesian point, tilt, width (length), height |
| *Opening* | Opening in a surface, such as a door or a window, etc. | Opening type, Id, geometry, description of opening, width and height |
| *Daylight Saving* | This depends on the weather in a region | Daylight savings are mentioned or not |
| *Zone* | A group of rooms located in a building that is served by the same HVAC plant or VAV box. Each zone may contain a group of spaces (or rooms) that have their own set of unique set of characteristics such as similar orientation or temperature set point. | Id, name, description, flow, airflow changes per hour, flow per area, flow per per-son, outside air flow, Design heating temperature, de-sign cooling temperature. |
| *Construction* | The type of composite construction (different layers) that makes up a wall, roof, floor, etc. | Id, U-value, Absorption, Roughness, Layer Id |
| *Layer* | Describes the material used in the layer | Layer Id and Material Id |
| *Material* | Describes the properties of materials which are presented in layers | Id, Name, R-value, thick-ness, conductivity, density and specific heat |
| *Schedule* | Defines the yearly wised schedule for occupants, equipment and lighting in a building space | Id, Type, Yearly schedule Id, Begin Date, End Date, name and week schedule Id. |
| *Week Schedule* | Defines the weakly schedule for occupants, equipment and lighting in a building space | Id, type, Day schedule Id, name |
| *Day Schedule* | Defines the daily schedule for occupants, equipment and lighting in a building space | Id, type, name and schedule values |
| *Document History* | Details about the gbXML file | Id, company name, GUID, product name, created by, etc. |
| *WindowType* | Defines the thermal properties of the window | Id, Solar Heat gain coefficient, U-value, Angle of incidence, etc. |

# 4 Research analysis – comparisons between standards and exchange data schema, and missing terms identification

After introducing the context of standards and technologies for information exchange and building representation, a series of analysis is proposed to assess the level of consistency and expressivity of the standard languages, aiming at providing a complete state of the art point of view on the semantics of building models.

## 4.1 Comparison on object definitions in ISO 12006-2 and IFC

In their work, Di Martino et al. (Di Martino, et al., 2019) proposed a critical comparison between ISO 16739 object definitions and ISO 12006 showing that different international standards define in different ways the objects used in the building of the data model, introducing an obstacle to the realization of a harmonised common exchange format. As previously described, the data exchange format standard is represented by ISO 16739 – *Industry Foundation Classes*, while ISO 12006 – *Building construction – Organisation of information about construction works* is identified as the reference for the mapping of terms. The analysis aims to discuss the bridge between part 2 and part 3 of ISO 12006, so between the frameworks for classification and object-oriented information. The first attempts of understanding this relationship were made in 2005 by A. Ekholm (Ekholm, 2005) who identified the differences in semantics and structure of the two standards in perspective of building an ontology for the AEC/FM sector. The intended purpose of ISO 12006 is to harmonize national and regional classification systems according to standardised rules. IFC, instead, initially rejected classification systems with the idea of representing elements in an open framework thanks to a common semantic. For this reason, it is necessary to agree on a standard generic domain model.

A first step of the analysis consisted in the comparison between the framework proposed in part 3 of ISO 12006 and the IFC architecture. The comparison was eased by the EXPRESS language in which the two set ups are written. EXPRESS-G graphs show even more easily the correspondence of IFC root entities and their relations to the ones standardised in ISO 12006. In this last standard the list of objects introduced, considering the objects and the objectified relationships, counts 40 elements, which is a quantity comparable only to the ones considered in the *IfcKernel*. Figure 10 and Figure 11, written in EXPRESS-G, allow a faster visual comparison between the two top level frameworks with root elements. Through the two figures it is possible to understand that in both cases the abstract root element is supertype of three elements, xtdObject, xtdRelationship and xtdCollection in ISO 12006-3 and IfcObjectDefinition, IfcPropertyDefinition and IfcRelationship in the case of IFC. While two out of three represent the same concept, the entities xtdCollection and IfcPropertyDefinition are one of the differences between the frameworks. The first one expresses a narrower concept, as it is defined as “a group or collection of things” (International Organization for Standardization, 2007) and it is supertype of specializations like xtdNest or xtdBag. The IFC equivalent entity is defined, instead as “the generalization of all characteristics that may be assigned to an object” (International Organization for Standardization, 2018a). In this case, this definition can be interpreted as a specification of an entity representing group of things, as in IFC grouping of elements are managed by the objectified relationships. In ISO 12006-3 the entity which relates an object with its properties is xtdRelAssignsProperties.

Since there is no core change between the considered versions of IFC, the comparison shows correspondence for both editions. The analysis went on comparing elements introduced in ISO 12006-2 and two different releases of IFC (IFC 2x3 and IFC 4 add1). These two versions of IFC were chosen according to their relevance in the industry at the state of the art. About ISO 12006-2, 2007 and 2015 versions were considered. Furthermore, ISO 6707 definitions were also compared just considering some basic terms of the industry.

Following the scope of ISO 12006-2, it is intended to guide the realisation of classification systems, starting from basic definitions and giving examples of object relating. In this sense, it has a narrower scope than IFC, as it also applies to both building and civil engineering works, in all their life-cycle phases, from briefing to demolition.

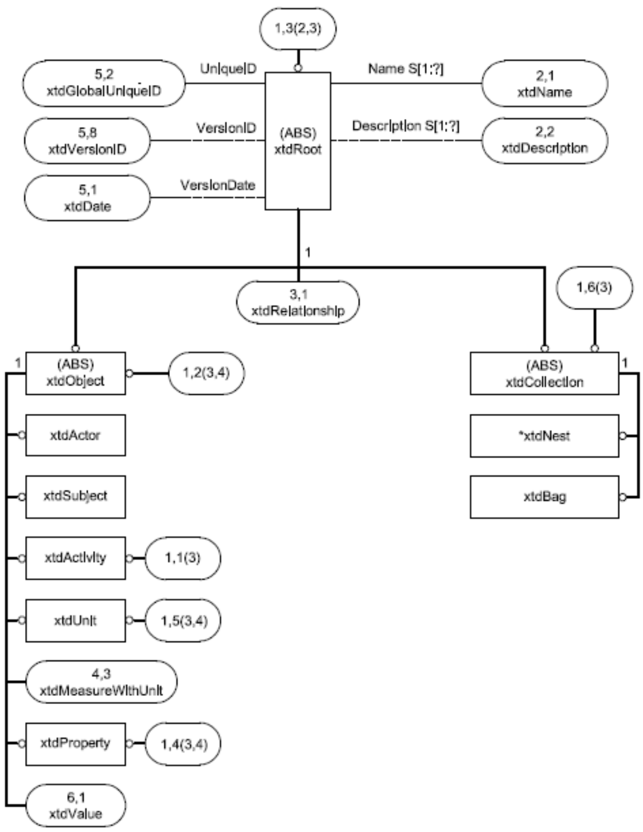


**Figure 11: ISO 12006-3 top level diagram (International Organization for Standardization, 2007)**

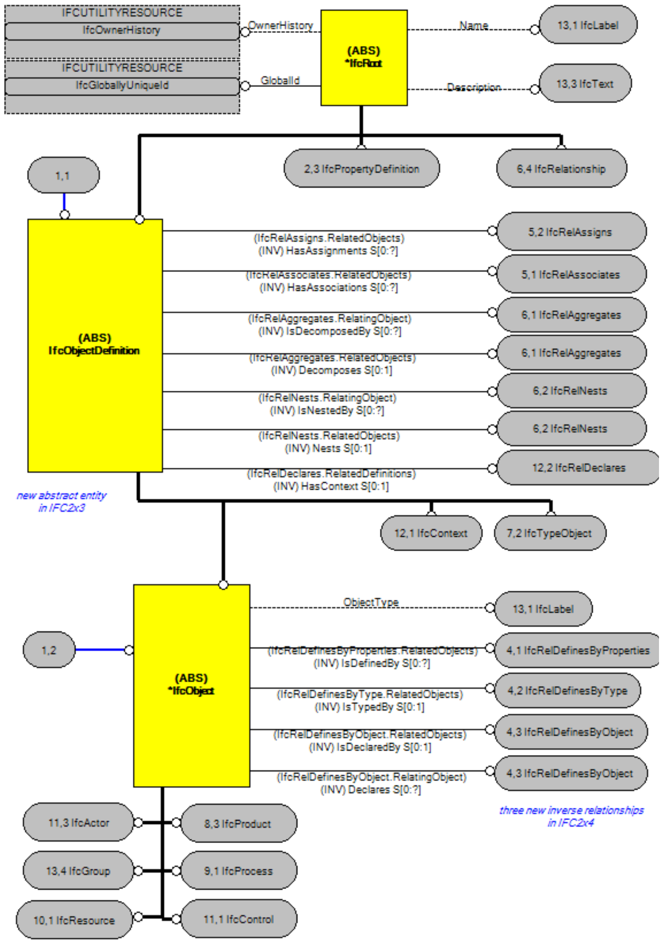


**Figure 12: ISO 16739 (IFC) top level diagram, part 1 (International Organization for Standardization, 2018a)**

On the other hand, IFC does not only define rooted and non-rooted classes, property and quantity sets, but it introduces classes with short definitions coming from either ISO 6707 or BuildingSMART (formerly IAI) working groups, then coded in ISO 16739.
ISO 12006-2:2007 defines a total amount of 20 objects, which have been searched throughout the collections of IFC 2x3 and IFC 4 (653 and 768 entities respectively). In 2007 edition of the standard, relations between the considered objects are not clearly defined, but it is possible to assume a link between the terms *construction resource*, *construction process* and *construction result*, as an example. The same concept (*process*), then, is differentiated between *construction process* and *work process* in ISO 12006-2. This mismatch leads to a conflict between the two active standards, as it is possible to understand from Figure 13.

| Item | UNI 12006-2 | | IFC | | | |
|---|---|---|---|---|---|---|
| | Term | Definition | Entity | Definition (from IAI) | Notes | % |
| 1 | Object | Any part of the perceivable world | IfcObject | Generalization of any semantically treated thing or process. Objects are things as they appear, tangible or non tangible | Supertype in IFC of Actors, controls, groups product and resources | 100 |
| 2 | Construction object | Object of importance to the construction industry | IfcProduct | Any object, or any aid to define, organize and annotate an object, that relates to a geometric or spatial context. Subtypes of IfcProduct usually hold a shape representation and a local placement within the project structure. In addition to physical products (covered by the subtype IfcElement) and spatial items (covered by the subtype IfcSpatialStructureElement) the IfcProduct also includes non-physical items, that relate to a geometric or spatial contexts, such as grid, port, annotation, structural actions, etc. | Object of importance may be represented both by IfcProduct or IfcResource | 25 |

**Figure 13: ISO 12006:2007 to IFC comparison (Di Martino, et al., 2019)**

| Item | UNI 12006-2 | | IFC | | | |
|---|---|---|---|---|---|---|
| | Term | Definition | Entity | Definition (from IAI) | Notes | % |
| 11 | Construction process | Process which transforms construction resources into construction results | IfcProcess | IfcProcess is defined as one individual activity or event, that is ordered in time, that has sequence relationships with other processes, which transforms input in output, and may connect to other other processes through input output relationships. An IfcProcess can be an activity (or task), or an event. It takes usually place in building construction with the intent of designing, costing, acquiring, constructing, or maintaining products or other and similar tasks or procedures | IFC definition is more inclusive than the one of ISO 12006 | 100 |
| 13 | Work process | Predominant construction process which results in a work result | IfcProcess | | Narrower concept, possibly subtype of "construction process", or viceversa | 50 |

**Figure 14: *construction process* and *work process* comparison (Di Martino, et al., 2019)**

In developing ISO 12006-2:2015, regulators tried to solve some of the issues of redundancy and to better link the definitions and the framework proposed in part 3, by introducing a draft schema of hierarchy for basic rooted elements. This helps the comparison between ISO 12006 and the IFC schema, as the difference between rooted and non-rooted elements is presented. Nonetheless, redundancies are still present, as many objects are strictly defined according to the design phase in which they are used, including in the definitions more constraints than needed.

## 4.2 IFC to Ontology: development of a representation of the IFC schema as ontology

The first attempt of using Semantic Web families of modelling for BIM models was proposed by Jakob Beetz in his doctoral dissertation (Beetz, 2009). The author states that the goal of the development of ifcOWL is to “”lift” the IFC model onto the level of ontologies” by adding semantic metadata. As already presented for ifcXML, part of the development consists in a mapping of the elements of the EXPRESS schema, then a second part describing the ontology schema. The translation of the IFC schema into an ontology was agreed in the LDAC2015 workshop among the members of the Linked Building Data community and documented in (Pauwels & Terkaj, 2015). The translations is based on three main principles:

- Keeping the well-known and established IFC schema for building representation;
- Enabling the features of Semantic Web technologies in the AEC field;
- Exploiting general purpose software implementations for reasoning and knowledge inference applications.

The process of development of ifcOWL[8] consists in replicating the existing IFC EXPRESS schema in an ontology in OWL language. The first one, defined in the standard ISO 10303-11:1994, introduces types, entities and properties and their relationships according to the EXPRESS schema (.exp). Every version of IFC has its own EXPRESS schema named as IFC2X3.exp, IFC4.exp, IFC4X2.exp, etc. The effort of representing as an ontology the IFC schema is limited to the framework of the standard, while other BIM related standards have not been represented in ifcOWL.

Semantic Web and its technologies share many of the goals of the formal expression of IFC, as it is intended to succeed the existing World Wide Web by describing any possible concept on the web with a modular and generic language. Web Ontology Language (OWL), as a consequence, is designed to be the basis for a network of diverse semantic domains, with the relations described with the principles of the RDF format. The RDF format is made of sequences of logical sentences in form of subject-predicate-object, known as *RDF triplets*. Every concept (subject, predicate or object) has a Unique Resource Identifier (URI) as label. Shortly, the OWL language allows concepts respecting the RDF format to create more complex statements and deeper class formulations.

The two specifications have different purposes: OWL is a description logic language to make concept definitions and to reason about them, while EXPRESS is a data modelling language more focused on questions of how to store and manage data related to the concepts in an information system. The expressiveness may be limited according to the purpose of the model. For example, it may be designed to contain more information or to be more performing, for this reason OWL has a set of restricted profiles (OWL2 EL, OWL2, QL, or OWL2 RL) that disable some representational mechanisms to make reasoning manageable. A substantial difference is made by the approach in the knowledge description, and it deals with the difference between closed world assumption (CWA) and open world assumption (OWA). CWA, frequently used in the development of common software applications including BIM tools and common relational databases, assumes that any statement that is not known to be *true*, must be considered as *false*. On the contrary, the OWA assumes that what is not known to be *true* is simply *unknown*. Semantic web technologies use this last approach; thus this change has been brought also in the development of ifcOWL, which still remains compatible with the CWA features of traditional software solutions. The declared criteria for the conversion procedure are here listed in order of importance:

[8] https://standards.buildingsmart.org/IFC/DEV/IFC4/ADD2_TC1/OWL/index.html

1. ifcOWL ontology must be in OWL2 DL;
2. ifcOWL ontology should match the original EXPRESS schema as closely as possible;
3. The primary aim of the ifcOWL ontology is the conversion of IFC instance files into RDF files.

The result of the first development of ifcOWL starting from the IFC4_ADD1.exp EXPRESS schema resulted in a converter respecting the criteria, but with few open issues to solve, such as the impossibility of conversion of RULE and FUNCTION declarations, LIST data types conversion issues and other topics regarding the expressiveness of the ontology and its modularity.

## 4.3 Missing terms and classes in ISO standards for renovation process scenarios

In this section, the information requirements for renovation process scenarios are compared to classes and properties of IFC schema in order to measure the obstacles for a full implementation of open BIM standards in such processes. Interoperability between built environment operators is handed by many factors, one of those can be identified in the expressivity of the IFC data schema. In many cases, authoring software solutions use a different store information in different formats and use different categories and relations, which result in unsolved issues at the moment of a model export in .ifc.

In the case of BIM4EEB, the different tools need particular sets of data for each purpose, but many times these aspects have not been matched with IFC developments. Two main actions have been activated: at first, the mapping of BIM4EEB specific information requirement and the consequent analysis of mismatches or missing classes or properties; secondly, an analysis of the state of the art in similar projects or research works. In this section it is possible to find tables and references to new classes and properties as drafted either in BIM4EEB or in other contexts. Such classes and properties are just proposed in this form, as the purpose of this section is to provide a basis for a proposal of improvement of the existing standards to be discussed and refined. Further on, data requirements collected from different tasks of the project will be useful for, at first, the development of the BIMMS and the ontology framework of BIM4EEB and, consequently, for the standardization activities of T9.3 and described in the report D9.3, as described in Figure 15.

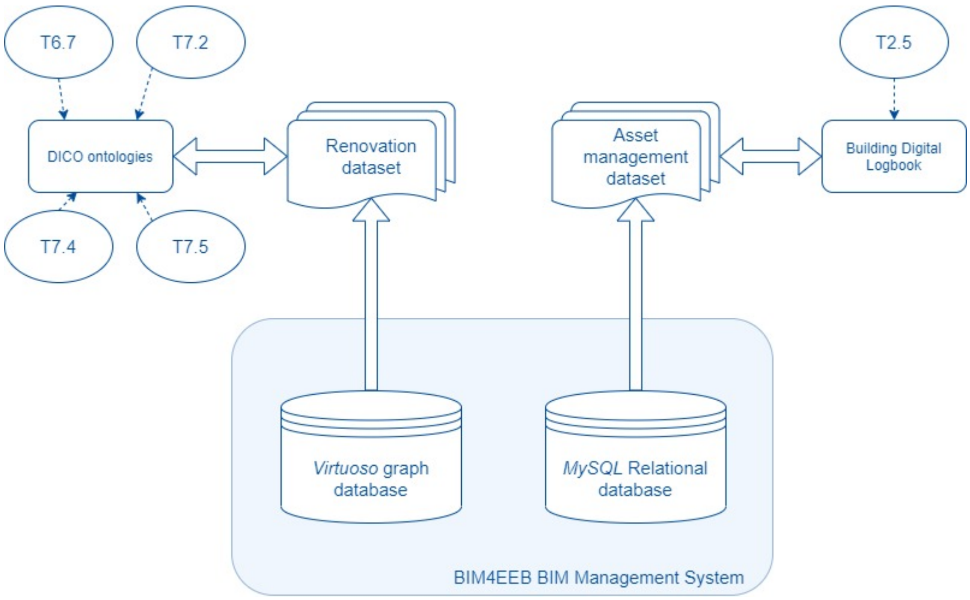


**Figure 15: Data requirements workflow of BIM4EEB**

### 4.3.1 BIM4EEB information requirements

The main source of information for the proposed analysis is Task 3.6 in which information requirements about different tools have been collected and mapped according to the developed ontologies and IFC standard. The data specification requirements have been listed and classified according to the use case scenario of application in the interface of the tools developed in BIM4EEB for a future use for standardization purposes. The list of use case scenarios is here listed:

- Performance evaluation system (T6.4);
- Renovation workflow management (T7.2);
- BIM assisted energy refurbishment tool (T6.6);
- Occupants profiling mechanism (T6.7);
- Prefabrication of exhaust air heat pumps in the renovation (T7.4);
- Design of prefabricated thermal insulation components (T7.5);
- Digital solution for linking product data to BIM during the procurement process of a contractor (T7.3).

These categories correspond to different task and tools that specifically deal with vertical issues raised by BIM4EEB partners, thus it does not aim to map and cover the defects found over the representation of a generic renovation process.

Most of the missing properties come from the data specification for occupant profiling mechanism, in which many comfort parameters, dealing with thermal, IAQ (Indoor Air Quality) and lighting descriptors are highlighted as the basis for the creation of the tool. Also, prefabricated thermal insulation component are not easily described considering IFC schema standardized in ISO 16739:2018. One of the weak points is related to the opportunity to describe renovation requirements as IFC objects don't allow an easy editing of properties. As a matter of fact, such properties are not defined universally when the model is created, both as-designed or as-built, but they are subjected to modification in time, causing substitution of objects or their relative parts. Renovation processes can include substantial changes to walls or systems; thus models should be capable of representing complex changes to the components of a building.

**Table 2: Missing terms and classes in ISO 16739 for renovation processes**

| ***Nr.*** | ***Object*** | ***Object property*** | ***Data type*** | ***Description*** |
|---|---|---|---|---|
| | | *Occupants profiling mechanism* | | |
| 1 | Location | Tdrybulb (8760) | Double | Real time dry-bulb temperature, Deg-C, for each hour |
| 2 | Location | RH (8760) | Double | Real time Rel. humidity of air, %, for each hour |
| 3 | Location | Air Quality (8760) | Double | Real time air quality of air, %, for each hour |
| 4 | ZoneSetPoints | HeatingSetPoint | Double | Heating set point in °C |
| 5 | ZoneSetPoints | CoolingSetPoint | Double | Cooling set point in °C |
| 6 | ZoneSetPoints | CO2SetPoint | Double | Maximum CO2-lev of the zone when CO2-controlled ventilation, in ppm |
| 7 | ZoneSetPoints | NightSetBackTemperature | Double | Set back temperature for heating between 10 PM and 6 AM |
| 8 | ZoneSetPoints | user/auto set | Boolean | Set point set by the user or the system (e.g. through a schedule) |
| 9 | RoomUnit | sensorType | enumeration | Air temperature, Operative temperature |
| 10 | Thermal Comfort | Indoor air average temperature | Double | Indoor air average temperature |
| 11 | Thermal Comfort | Working average temperature | Double | Working average temperature |
| 12 | Thermal Comfort | Average relative humidity | Double | Average relative humidity |
| 12 | Thermal Comfort | Air speed | Double | Air speed |
| 14 | Thermal Comfort | Average rate | Double | Average rate |
| 15 | Thermal Comfort | Unsatisfied percentage | Double | Unsatisfied percentage |
| 16 | Visual Comfort | Average illuminance | Double | Average illuminance |
| 17 | Visual Comfort | Daylight factor | Double | Daylight factor |
| | | *Design of prefabricated thermal insulation components* | | |
| 1 | Wall | Skewness | Varchar | Dimension and position of max skewness of the wall, measured in mm/m |
| 2 | Wall | External finishing | Varchar | Type of external finishing and thickness |
| 3 | Wall | Structural resistance | Varchar | Traction and compression values of non-structural elements |
| 4 | Accessibility | street accessibility | varchar | access to construction site |

| | | | | |
|---|---|---|---|---|
| 5 | panel | number of sides | INT | number of sides of the panel (depends on the shape) |
| 6 | panel | rectangular | BOOL | yes / no (other shapes: trapezoidal, triangular?) |
| 7 | panel | angles | double | angles between each couple of sides (all 90° for rectangular panels) |
| 8 | panel | dimension | varchar | panel size per type (length of sides) |
| 9 | panel | joint | varchar | width of joints |
| 10 | panel | anchors | varchar | position and number of anchors |
| 11 | building | edge number | INT | total number of edges for each facade |

This list considers just part of potential missing requirements for renovation scenarios, but it integrates contribution from BIM4EEB tasks dealing with the use case scenario listed above. Other relevant aspects of integration have been searched in similar projects described in literature.

### 4.3.2 Relevant projects and research efforts

The IFC schema is intended to represent the built environment generically for the exchange of information in the construction or facility management industry sector. Many other fields, though, could benefit from the use of a standardized format for different operations and purposes. For example, standardisation efforts like COBie have proved a strong interest for the operational phase of the building life cycle, by creating a Model View Definition for the IFC schema delivering asset data without geometric description. In this chapter some examples of research items in different field of study are presented, highlighting existing entities and their specialistic use but also weak points of IFC standard schema for particular disciplines.

BIM and GIS integration is a great topic of interest in research, as the integration of the two methods can produce many advantages to construction processes. Karan et al. (Karan, 2015) investigated pre-construction planning issues, proposing and validating with two use cases a methodology to enhance interoperability between these domains. GIS can offer a wide framework for use of spatial data and relationships contained in BIM models, for the purpose of logistics or safety purposes, or also to act on closeness/remoteness optimization of building placement. One of the key elements for the integration of the information referring to these different domains is the geo-reference of BIM models. Buildings are usually represented in local 3D coordinate systems, while GIS data are always geo-referenced in 2D or 2.5D. The only link between different coordination systems in IFC has been introduced in the standard version of 2013, where the object *IfcCoordinateReferenceSystem* has been introduced as a refer for interpretation in the case of using the IFC protocol as import into a software platform. An integration of the two datasets can be done through semantical enrichment of the databases behind BIM and GIS. From the BIM point of view, researchers have noted that topography objects are not adequately defined in BIM models. As an example, even if data describing topography are transferred through standardized or commonly used formats like CSV, BIM platforms and the IFC schema model different GIS classes (bare ground, vegetation, body of water, noise, etc.) as the same object, considering just superficial descriptions of sites. Also, other researches (Nagel, 2009) have highlighted another great difference in the modelling approach between BIM and GIS: building models are created following a generative approach based on building elements, describing then volumes and spaces created by the relations between such elements;

GIS modelling, instead, are based on topography description, generating models of visible surfaces and adding data with an accumulative approach, as shown in Figure 14.

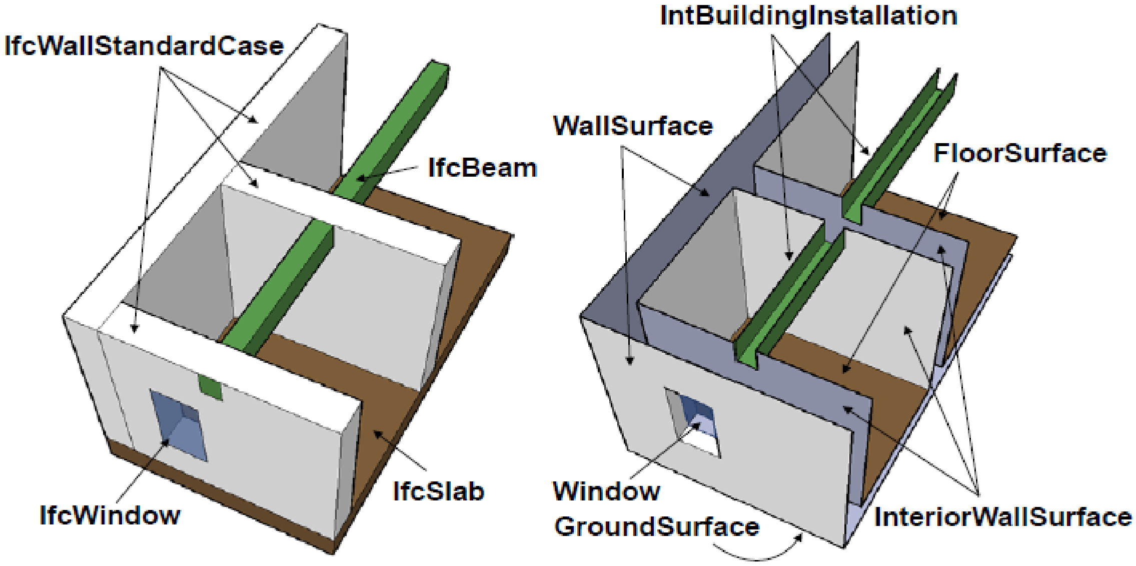


**Figure 16: Building representation in BIM (left) and GIS (right) (Nagel, 2009)**

All the cited works show in the conclusion how important a harmonization and enrichment of the semantics of building models can ease the interoperability between BIM and GIS domains, but root differences in defining spaces and objects are still present in the latest editions of the relative standard models.

The topic of Building Energy Modelling (BEM) is a key aspect of renovation processes, and it plays a pivotal role in the work of BIM4EEB. The holistic approach behind this project aims at collecting in the same place, in the CDE, data gathered from users, owners, sensors, building components, energetic systems, and to use them to create models able to predict and indicate the best strategies for energy retrofitting of buildings. Many of the cited inputs for building energy simulation software solutions are coming from building models in IFC formats, though the preparation of a BIM for an energy analysis is still addressed as a time-consuming activity. Alsharif (Alsharif, 2019) reviewed the existing techniques of automated application of BIM-based energy analysis using open formats. Among the discussed formats, IFC and gbXML schemas are the main refer for the comparison in this work. According to the author, the main interoperability challenges are identified in five different classes, here listed:

- Location: the geo-reference of BIM models should be exploited as much as possible for BEM purposes. Some data from weather data repositories (e.g. in .epw format) can be included in IFC;
- Geometry: Complex geometries and room boundaries have been highlighted as objects of improvement considering IFC files;
- Material properties: some parameters (e.g. IR absorptivity, density, thermal conductivity) are not present or not easily interpreted from the IFC schema;
- Building systems: IFC format lacks entities representing complex or advanced systems for energy conversion or distribution (e.g. heat pumps and combined heat and power (CHP)), besides system functioning schedules;
- Building operation: few operational data are represented in IFC schema.

Some of the problems pointed out by Alsharif could find a solution with the enhanced expressivity and linking capability of Linked Data approaches described before, although IFC still lacks entities to better represent buildings.

Asset information management, also, profits from enhancements in interoperability between building models and maintenance budget models. Moretti et al. (Moretti, et al., 2018) discussed the topic starting by investigating the use of the standard IFC model for facility management (FM), with the OpenBIM model as the central repository for budget definition. The core entity in this work is IfcAsset, as it can represent, according to ISO 16739, “a uniquely identifiable grouping of elements acting as a single entity that has a financial value or that can be operated on as a single unit” (International Organization for Standardization, 2018a). This definition helps in filling the gap between the modelling principle of BIM as an object-oriented model, and the FM models defined as cost-oriented through the use of the *centres of cost*. In their project, Moretti et al. applied these methods to find a maintenance budget appraisal, measured with the Facility Condition Index (FCI), calculated as the ratio between the cost of maintenance calculated at the moment of assessment and the Current Replacement Value (CRV) of the asset. The FCI index, then, has been calculated starting from the data stored in the IFC model. For doing this, the assets of the maintenance budget assessment have been exported into an IfcAsset entity and coupled with its own parameters and parametric sets like PEnum_MaintenanceType, PEnum_PriorityType, and maintenance operations have been described with the entity IfcProjectOrder, as shown in Figure 17.

| *Entity* | | *Name* | *Maintenace operations* | | | | |
|---|---|---|---|---|---|---|---|
| | | | *Cleaning* | *Revision* | *Light Repair* | *Medium repair* | |
| *Project Order (IfcProjectOrder)* | *Attributes* | Predefined Type (IfcProjectOrderTypeEnum) | MAINTENANCEWORKORDER | MAINTENANCEWORKORDER | MAINTENANCEWORKORDER | MAINTENANCEWORKORDER | … |
| | | Status (IfcLabel) | PLANNED | PLANNED | PLANNED | PLANNED | … |
| | | Long Description (IfcText) | Pulizia lato esterno dei vetri e della struttura con detergenti appositi | Revisione montanti e traversi in alluminio, cerniere e gurnizioni | Piccole riparazioni di infissi in metallo, compresa raddrizzatura di bordi, regolazione della chiusura, | Medie riparazioni di infissi in metallo, compresa raddrizzatura di bordi, battute, montanti, | … |
| | *Pset_ProjectOrderMaintenanceWorkOrder* | Work Type Requested (IfcText) | Light intervention | Light intervention | Light intervention | Medium-level intervention | … |
| | | Contractual Type (IfcText) | Global Service contract | Global Service contract | Global Service contract | Global Service contract | … |
| | | Maintenace Type (PEnum_MaintenanceType) | SCHEDULED | SCHEDULED | SCHEDULED | CORRECTIVE | … |
| | | Fault Priority Type (PEnum_PriorityType) | LOW | MEDIUM | MEDIUM | MEDIUM | … |
| | | Location Priority Type (PEnum_PriorityType) | LOW | LOW | LOW | MEDIUM | … |
| | | Scheduled Frequency (IfcTimeMeasure) | 12,0 | 24,0 | 24,0 | 36,0 | … |
| *Cost schedule (IfcCostSchedule)* | *Attributes* | IfcCostScheduleTypeEnum (IfcCostScheduleTypeEnum) | ESTIMATE | ESTIMATE | ESTIMATE | ESTIMATE | .. |
| *Cost Item (IfcCostItem)* | *Attributes* | Name (IfcLabel) | Total cost | Total cost | Total cost | Total cost | .. |
| Cost Value (IfcCostValue) | Attributes | Applied Value (IfcText) | 5.000,00 | 12.312,00 | 22.707,00 | 20.277,00 | .. |
| | | Cost Type (IfcLabel) | NULL | NULL | NULL | NULL | .. |

**Figure 17 List of IFC entities used in the FCI index calculation (Moretti, et al., 2018)**

Results showed a great efficiency of the BIM model for the purpose of the study, still highlighting that on this format different proposal could ease the process of budget assessment, in particular considering the enumeration type entities that could be enlarged for a better representation of maintenance strategies.

In 2017 Krijnen and Beetz (Krijnen, 2017) proposed an IFC schema extension integrating point cloud data sets. BIM4EEB is also developing a fast-mapping tool in WP5 to create a BIM model of existing buildings. Point cloud data models are large sets of unstructured 3D points describing volumes by surfaces of scanned objects. It is an output of tools like laser scanning or photogrammetry, as an example. IFC can offer the gathered data a meaning thanks to its semantics. Authors highlighted eight main reasons for the implementation of point cloud data in the IFC representation:

1. The storing on the same file of rich IFC data and detailed geometric models allows a faster and less time-consuming management of project information;
2. The semantic base of IFC objects allows a better use of point cloud data, describing building elements after an automated or semi-automated object recognition phase;
3. IFC object classification helps in retrieving localized point datasets;
4. Point cloud data can help in recognizing differences between as-built and designed models;
5. Detectable deformations or other structural problems can be detected by comparing different point cloud datasets obtain regularly for maintenance assessment. It can also make more accurate definition of structural loads thanks to the deformation evidence measured;
6. In the field of infrastructures, in particular considering linear infrastructural elements, point clouds obtained from air are a fundamental element of the design process. Thus, it can be considered an optimal bridge for the extension of the IFC model to the domain of infrastructure works;
7. Point clouds can detect precisely small works and small scale geometries. This is helpful in the management of HBIM
8. Buildings and infrastructures have a long life cycle; thus it is important to guarantee interoperability over these periods of time.

Drawbacks too are highlighted in this paper, as the authors suggest that in real scenarios the implementation of point cloud data would bring to an increase of size of models, and they would need another format (HDF5) in order to store datasets of different nature and typical size. IFC includes entities that may represent point clouds in its native format, but points are represented in the IfcBlobTexture in bi-dimensional environment with a bitmap approach, making the exchange and use of such files complex and time-consuming. As a matter of fact, when it comes to convert point cloud data into BIM formats, the risk of losing information about colours or normal vectors is high, but also metadata about the capturing process (humidity, temperature, capturing dates, etc.). An immediate semantic association of points to building elements would also allow controls over the coverage of the scanning procedures over the investigated surfaces. Serialization formats included in the active standard framework are described by ISO 10303-21 - *Industrial automation systems and integration — Product data representation and exchange — Part 21: Implementation methods: Clear text encoding of the exchange structure* (International Organization for Standardization, 2016a). This standard was developed favouring data exchange over storage efficiency, in fact the same number would be weight twice the bytes of a point represented according to IEEE 754 (IEEE, 2019). Other ways of linking point cloud datasets through external links or other formats would result in inefficient representation. For this reason, the authors proposed an extension of IFC schema capturing the point cloud data and allowing a fast and easy storage of such datasets. The proposal is published on an open repository[9]. It consists of a new set of entities, starting from IfcPointCloud introduced as sub-type of IfcRepresentationItem. Authors also suggest, along the entity parameters, to indicate the Level of Detail (LOD) of the required representation, in order to allow an incremental resolution of the dataset. The new element should be able to represent also vectors and colours of the surfaces investigated. Following the typical IFC structure, IfcPointCloudElement is introduced to link several IfcPointCloud, in particular when the datasets are various and with no explicit association. The proposed property set for point cloud datasets PSET_PointCloudCommon is shown in table 3.

**Table 3: PSet_PointCloudCommon property listing (Krijnen, 2017)**

| Name | Property type | Data type |
|---|---|---|
| SensorVendor | IfcPropertySingleValue | IfcLabel |
| SensorModel | IfcPropertySingleValue | IfcLabel |
| SensorSerialNumber | IfcPropertySingleValue | IfcLabel |
| SensorHardwareVersion | IfcPropertySingleValue | IfcLabel |

[9] https://github.com/DURAARK/IFCPointCloud

| | | |
|---|---|---|
| SensorSoftwareVersion | IfcPropertySingleValue | IfcLabel |
| SensorFirmwareVersion | IfcPropertySingleValue | IfcLabel |
| Temperature | IfcPropertySingleValue | IfcThermodynamicTemperatureMeasure/ THERMODYNAMICTEMPERATUREUNIT |
| RelativeHumidity | IfcPropertySingleValue | IfcRatioMeasure |
| AtmosphericPressure | IfcPropertySingleValue | IfcPressureUnit |
| AcquisitionStart | IfcPropertyReferenceValue | IfcDate |
| AcquisitionEnd | IfcPropertyReferenceValue | IfcDate |

Authors also suggested methods for the serialization of point cloud datasets that wouldn't overweight on IFC storage capabilities. The method indicated deal with description of points on a parametric surface (planar segmentation): this allows on one side to reduce the dimension from three coordinates in a cartesian system to two on a known surface; and on the other side to allow a first categorization of the dataset preparing it for object recognition.

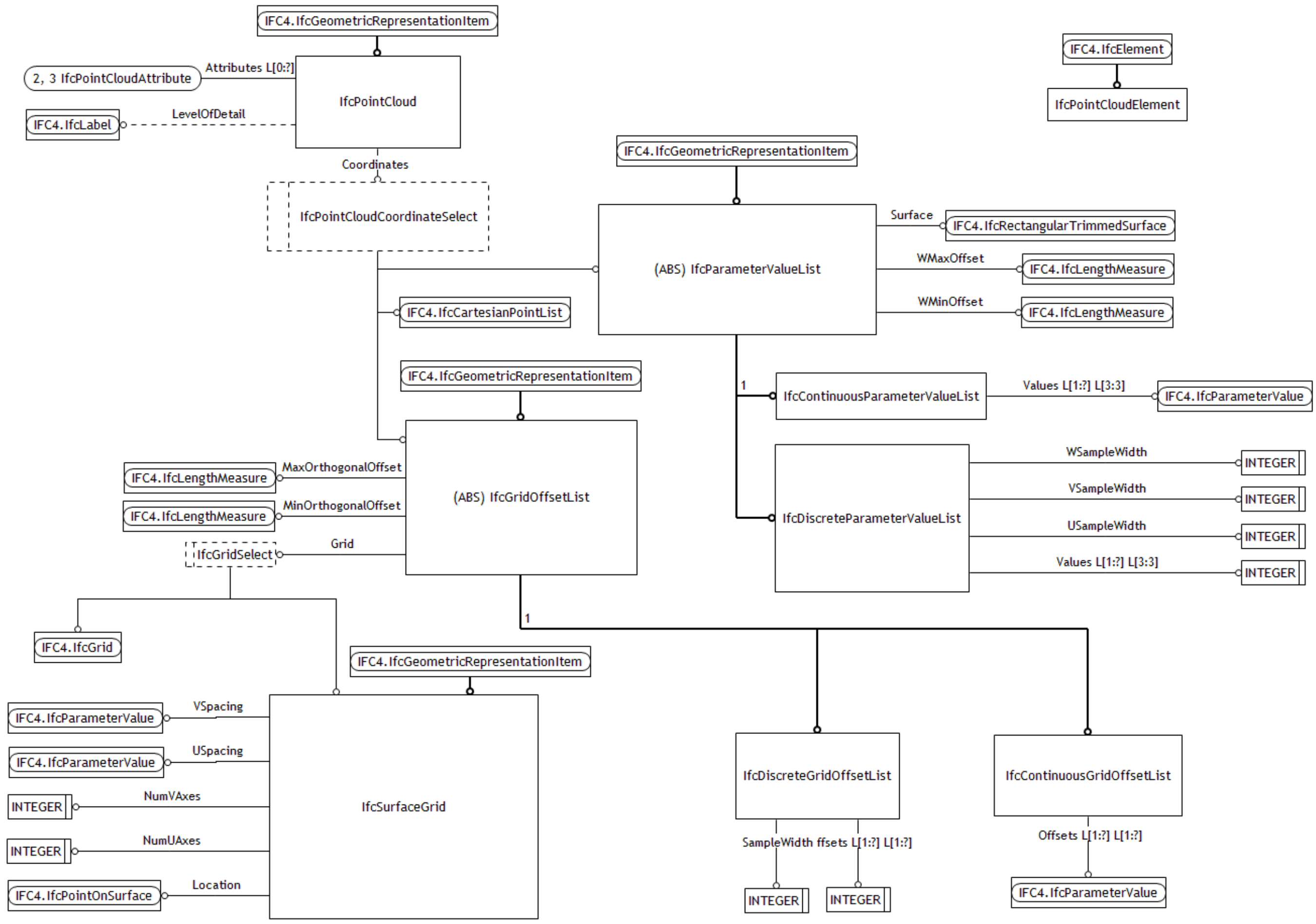


**Figure 18: Main schema of IfcPointCloud (Krijnen, 2017)**

## 4.4 IFC vs gbXML

The functionalities, structure and schematic representations of the data exchange formats gbXML and IFC are clearly explained in the previous chapter of this document. Apart from their individual functionalities and capabilities, this section focuses on a small comparative analysis on both gbXML and IFC meta-data formats. This analysis focuses mainly on the data representation and holding capabilities of both the schemas. A small comparative table is indicated below with the incorporation of analysis results. Before going into the more specific comparative analysis, it is most import to mention that gbXML is only designed to transfer data related to Energy Performance Simulation domain. So, the structure of the gbXML is very simple and designed hierarchy only represents the components needed for the energy simulation. On the other hand, IFC has capabilities to perform interoperability between several domains, for example, structural engineering domain, energy analysis domain, information management and bridge engineering domain, etc (Karlapudi, 2018). It is a very complex structure with the capabilities of holding most amount of data related to all these domains.

**Table 4: Comparative analysis between IFC and gbXML**

| IFC | gbXML |
|---|---|
| Structural serialization is based STEP physical file format and the model representation is based on EXPRESS file format. The serialization can also be represented in IFCXML file format. | The data serialization is only available in XML format. |
| Complex structure, which enables to hold data from the different domains. | Simple structure, which supports data only related to energy simulation domain. |
| Follows the concept of inheritance to enable the data represents and holding concepts inherit from the parent entity to child entity. | No concept of inheritance |
| Relations between the objects can be performed by using the concept of objectified relationships. This is also one of the reasons to makes the structure little more complicated, but it is efficient to make relations between the major numbers of involved objects. | Relations based on the ID's defined for each object in the model |
| Support the representation of the as-is model. I.e. supports the 3-dimensional objects as it is. | Does not consider 3-dimensional model objects. This schema only considers inner surfaces and the surface at the centreline of the object. This transfer of the 3D object to the 2D surface process needs end model corrections in the simulation tool. |
| Specifically, in the energy simulation, the objects only bounded with the spaces are considered. The other shading objects which are not bounded by the space are ignored. In IFC, for example, the shading portion of the wall is also treated with Ifcwall entity. No particular entity for defining the shading surfaces in the IFC schema. | According to the schema, objects bounded by the space are space boundary objects and which are not bounded is treated as surface elements. Both the bounded surfaces and shading surfaces are transferred to the simulation engine. |

(Karlapudi, 2018)

## 4.5 Analysis summary

As explained in the introduction, chapter 4 aims at assessing the level of consistency and expressivity of the standard languages to provide a complete state of the art point of view on the semantics of building models. The chapter has been divided in different subsection to analyse through specific comparisons different areas of the standard languages, namely:

- ISO 12006-2 and IFC
- IFC to ontology
- IFC and gbXML

The analysis developed in the first area of study, combined with the results of the previous works developed in the BIM4EEB project, resulted in the identification of the missing terms and classes in the ISO standard with specific reference to the renovation processes scenarios that represent the focal point of the project.

Hence, chapter 4 clarify what available standards exists and what are the limitations that the current framework has when looking at the development of renovation works. The results of this analysis will be used in the next chapters to identify the recommendation for the use of exchange formats in the BIM4EEB project (chapter 5) and the perspectives for the integration of this results in the ongoing standardisation activities.

# 5 Recommendations for the use of exchange formats in BIM4EEB

Interoperability in AECO sector is a key topic for the integrated implementation of BIM methods. New challenges of building modelling, represented in BIM levels in Figure 18, will change the focus from domain specific models, objects stored and classified in libraries (known as “Full collaboration” level) to web-stored linked data (known as “Full integration” level). This change needs a different technology approach and technological development for a deep implementation. Currently, information is stored in models that can be exchanged between building owners, designers, operators, etc. These datasets are usually developed with authoring software tools and closed formats. BuildingSMART (formerly IAI) developed a common format to exchange data based on STEP format, standardized in ISO 10303. In this chapter suggestions for the enhancement of data models and its related formats are presented, starting from the analysis made in the context of this task, over the whole WP3 and also considering efforts reported in the literature.

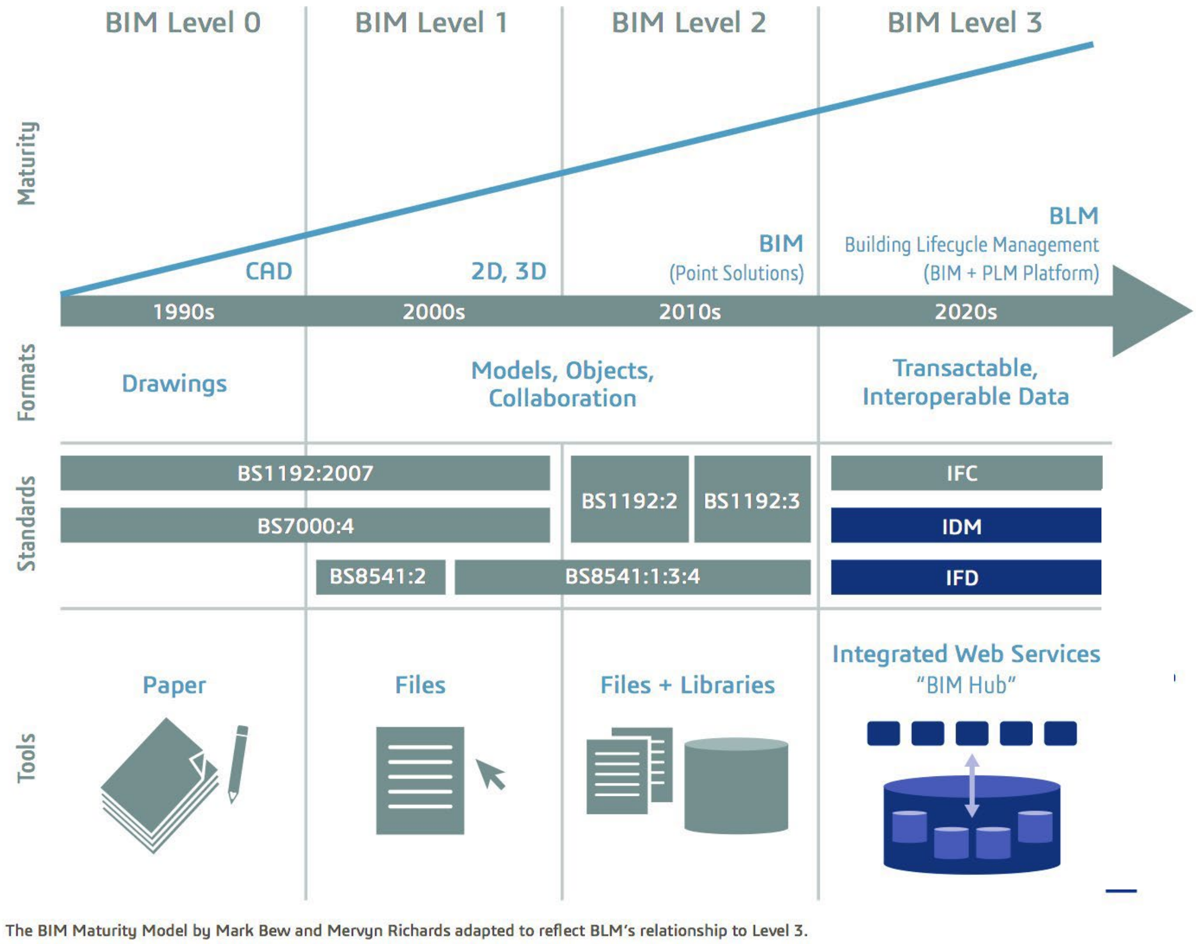


**Figure 19 Building Information Modelling levels (Shayesteh, 2015).**

On the one hand, Linked data allows a great interoperability between users but also between domains which share a semantic base. On the other hand, the most common format for information exchange, as previously said, comes from the IFC schema and it is written in EXPRESS language. When compared to OWL, different constraints and modelling principles arise between the two models. Linking RDF graphs to existing exchange formats is one of the main issues, together with the one dealing with the creation and storage of URIs for building models.

The proposed analysis highlights two main dimensions that must be considered, i.e. the structure of exchange data models and the processes that their use require. As previously said, the relation between existing exchange data models and the RDF schema represents one of the main issues in the linked building data approach. This can be related to both the difficulty in creating a coherent match between the two structures and to the process required to obtain the final RDF model. In the following paragraph these two dimensions will be discussed and analysed to identify proposals to improve the existing exchange formats context.

## 5.1 Procedural perspective

The current approach in the development of information in a BIM approach requires the development of information models starting from one or more authoring tools, i.e. tools able to generate building information models. There is a vast selection of tools each one defined according to a specific data structure and a specific semantic structure. The exchange processes are fundamentally based on translation processes that can report the information fields of the starting model (native model) to the standard information fields of the selected exchange format. Looking to the IFC format, this approach is also related to its intrinsic structure, e.g. the possibility to act modifying the model. Figure 19 reports the information sharing process based on the IFC format. It aims to highlight the need to communicate the information to the responsible subjects of the native model in case of required changes. Thus, the information process should be considered in a circular way understanding how to communicate efficiently not only the model information but also the required changes and/or additional information to be included in the model itself. This approach, that is the need to create a circular process through review and acceptance of information models at the different levels of the collaboration chain, is aligned with the principles of ISO 19650 with particular reference to its part 2.

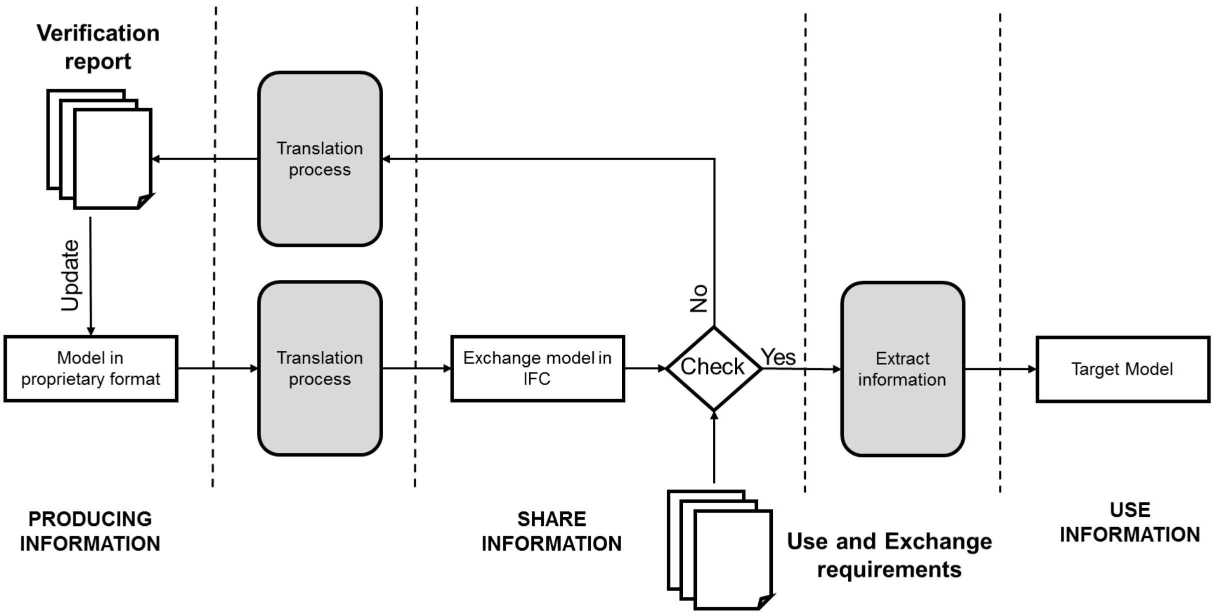


**Figure 20: IFC-based information sharing process (Mirarchi, 2019)**

Moving from the IFC approach to the Linked Building Data one, the procedural structure is even more complex in the existing industrial context. While most of the BIM authoring tools are able to export their models to the IFC format, this is not true in the case of the RDF one. Thus, the translation process from the model in its native format to the final RDF based environment usually involves two passages that are from native to IFC and from IFC to RDF (Figure 20). In a dynamic work environment characterised by a high number of changes that many times need to be performed in restricted period of time, this approach can hinder, if not well prepared, the use of linked data in the industry.

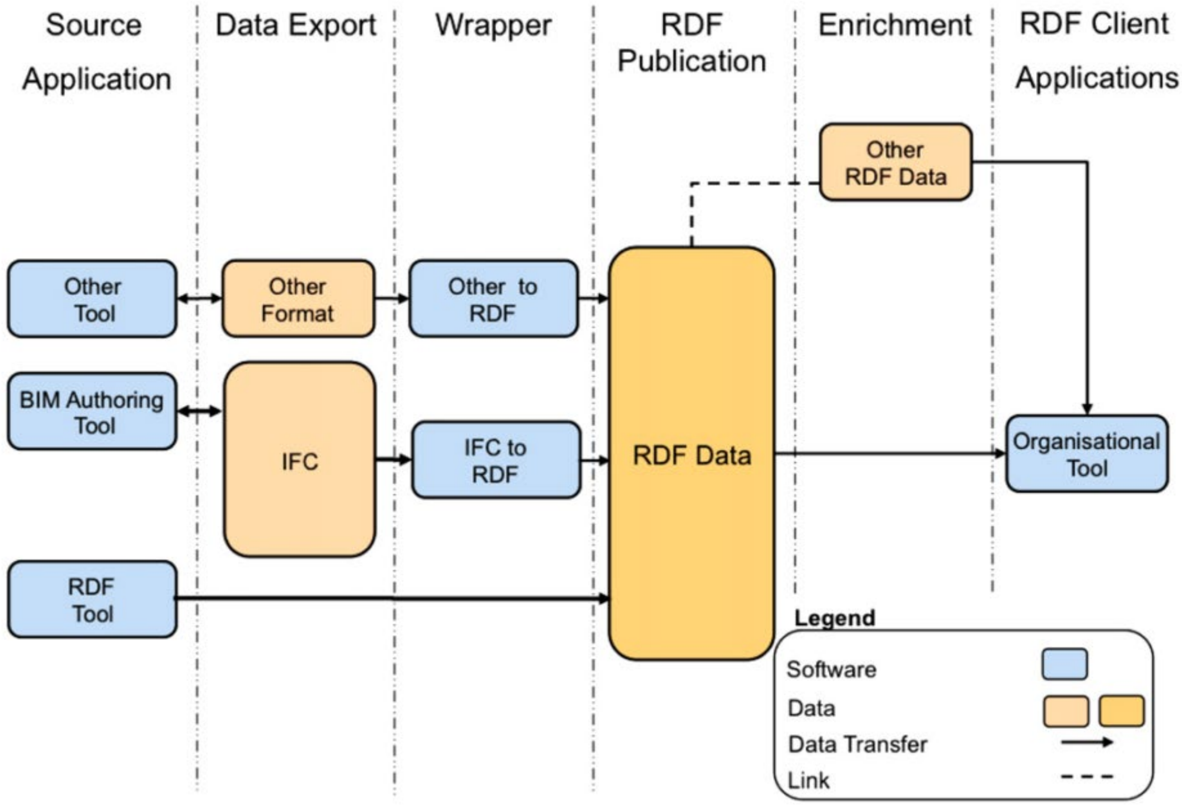


**Figure 21 Process for the use of an RDF based environment for the information integration from different sources (Curry et al., 2013)**

Furthermore, this double translation process can increase the difficulties in finding a coherent semantic representation.

Hence, the development of exchange formats should be related to its processes of use guaranteeing at least the following aspects:

- A clear process in terms of where information is generated, who and where can be modified, how to communicate surrounding information.
- A unique translation process able to admit circular changes to the information models.
- Alignment with the competencies of the industry stakeholders (i.e. processes that can be performed by the "standard" users).

Starting from these requirements, the process presented in Figure 20 should be modified including specific components that can overcome the above-mentioned limitations. A couple of observations can be made. Firstly, BuildingSMART is working towards a goal that the future versions of IFC, starting from IFC5, would be language neutral. The schema would be maintained in UML, from which it would be exported to different languages, one of which could be OWL. While the future of this development is still quite uncertain, if successful, in the future it could enable the direct export of IFC-compliant RDF from BIM authoring tools. Secondly, all IFC exports – regardless of the serialization format – are just exports; the native format of a BIM authoring tool can be quite remote from the conceptual structure of IFC. As a result IFC is mostly used as a read-only format, since importing a modified IFC file – so-called roundtrip –is difficult without information loss or significant restructuring of the original model. Fortunately, Linked Data technologies have an important advantage that could partly reduce the need to change the contents of IFC files when new information needs to be provided about the IFC entities that they contain. In Linked Data approach new information can be linked to the existing entities in a separate dataset, without touching the IFC file itself. Such interlinked enrichment datasets could be exchanged together with the IFC file in an ISO 21597 ICDD container.

In detail, it should be integrated with an IFC editor able to admit the creation of a circular process based on open formats and an easy to use interface that can be used by the industry with no need of specific knowledge on the IT side. The next Figure 21 reports the process that should be used in the development of the BIM4EEB BIM management system (BIMMS).

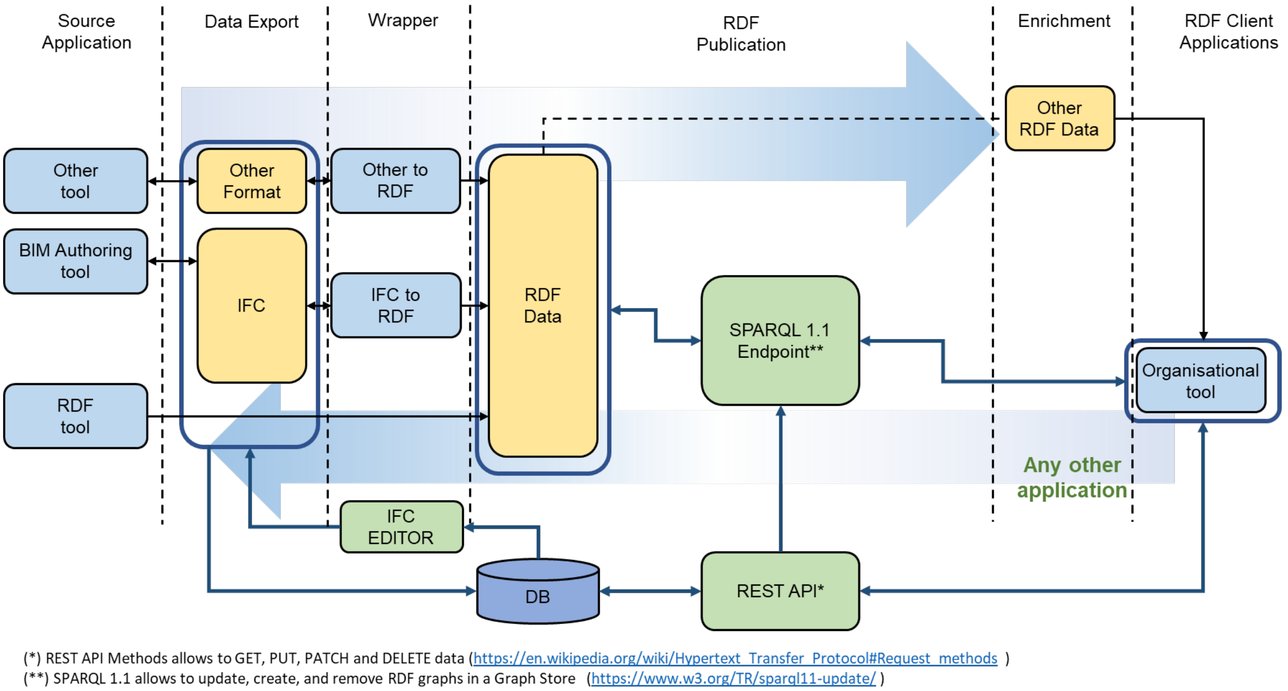


**Figure 22: proposed process for the development of the BIM4EEB BIMMS**

## 5.2 Data model perspective

As briefly explained in the previous paragraph, information exchange processes are mainly based on a translation action between proprietary data models to standard data models. The extensive analysis proposed in this document highlights a set of incoherence between the existing terms defined in the standard formats. Of course, this aspect is even worse when e.g. the IFC structure is compared to the structure of one proprietary format.

The differences in terms of number and type of classes, information fields, topological rules, etc. combined with the fragmented picture analysed and with the number of missing terms usually required by construction processes (here with particular reference to the renovation ones) represent some of the main limitations in the definition of a shared exchange approach. In fact, even if referred to a common exchange format (IFC) each project requires the identification of ad hoc rules and thus ad hoc translation processes that runs only in the specific project context hindering the possibility to communicate outside the project itself. This is of course in contrast with the use of linked data and requires attention in the definition of future exchange data models.

Hence the need to promote the work on the existing standards related to open formats to remove the existing discrepancies (see the analysis reports in the previous chapters of this document). On the other hand, according to the process perspective described in the previous chapter, the data model perspective can be integrated in a collaboration system that can provide a shared structure used by all the stakeholders involved in the process. In this direction, the BIM4EEB project should develop an integrated BIM management system that starting from the processes above described is able to define a shared data structure that can be used in the context of renovation works overcoming the limitations related to classes definition, parameters definition, etc. in proprietary and/or open formats.

## 5.3 Conclusions

The overview proposed in this document combined with the synthetic analysis proposed in this chapter highlight a complex framework of standards, technologies, dictionaries, etc. many times in conflict with each other. Moreover, due to the different development velocities of technologies, standards, industry needs and comprehensions, etc. the picture appears even more fragmented. It is difficult to identify a common line both in terms of semantics and processes of use.

With specific reference to the analysis proposed in the previous sections of this chapter, it is clear the need to propose a holistic overview according to the recent technological developments and requirements clarifying the application domain to guarantee an ontological and semantic structure able to create a common ground for data exchange (thus avoiding the proliferation of ad hoc solutions that requires a continuous action of alignment and translations in the exchange process). The procedural dimension has to be considered as a crucial point in these developments guaranteeing applicable solutions in the industry context of reference.

This action, that can find in the results of BIM4EEB project a useful knowledge base, should act as facilitator to promote the updates of the existing standards, data schema, etc. in an organic way to remove the existing discrepancies and guarantee a coherent common ground of cooperation. Moreover, the increasing need to relate the construction sector products (building, infrastructure, etc.) to the uses of these products including commercial activities, inhabitants, etc. requires opening the analysis to the existing frameworks from other sectors.

In the context of the BIM4EEB project, the development of the BIM management system and the related toolkit can address the limitations highlighted in the analysis provided in this document. Of course, it provides a possible solution in the specific context and according to the objectives of the project and does not remove the need of exploiting the results towards the entire sector considering the possibility of pushing the considerations expressed in this document to the relevant standard bodies (as explained in the next section).

# 6 Integration of BIM Standards for sharing information

As pictured in Figure 5, the framework of standards in the field of BIM and BIM data exchange is wide and fragmented. Old standards have been reviewed and republished even if other documents discussed the same topic or advanced towards new representation approaches. As an example, this is the case of ISO 10303-225 and ISO 16739, or the CAD set of standards ISO 22014 including reference to BIM models, defined in IFC and other documents. Nonetheless, IFC still represents a solid mean for information exchange in the existing AEC sector. This is the main reason why the introduction of a newly developed format would hinder all the advantages made on the issue of interoperability, from the point of view of authoring software solutions integration, operators training on open formats, software testing and developing, et cetera. This document aims to show (1) the relevance of topics to be included in BIM standards framework in order to represent new concepts and models proposed in research literature and (2) how these standards could be harmonized in less documents or sections in order to clearly define how to represent, organize and exchange the right information in the correct context.

Chapter 4.3 of this document introduces the research projects, including BIM4EEB, that dealt with the IFC data schema and its limit of representing common scenarios or the ability to store data from different domains. Some of those projects have produced a list of objects and properties that could represent disciplines that could profit from a deeper use of BIM tools. Efforts like the bSDD can be seen as tools for the integration and the update of entities in the IFC data schema, although the workflow for evaluating and including external definitions into the schema has not been standardized yet. As an example, one of the advantages of this tool is that data dictionaries coming from different sources, which are structured upon URIs on existing ontologies, can be easily aligned and integrated. Also, the application of Linked Data in construction is a topic of research that has been investigated since the last ten years and it has proved a great efficiency in data querying and management, but also in terms of interoperability. Digital Construction Ontologies have been specified by BIM4EEB to provide definitions to central concepts of ISO 19650 – from Built Asset, Appointment, and Delivery Team to Information Model, Information Container and Delegation. The concepts of Information Model and Information Container have also been aligned with ISO 21597 ICDD to facilitate information exchange as containers of multiple interlinked content entities.

For these reasons BIM4EEB activity aims at giving proof of the validity of these theses by suggesting the integration of a framework of ontologies in the standards for building information exchange. Finally, this deliverable shows the limits of the application of existing BIM standards to a renovation project, which represents a considerable share of building works in the AEC field in Europe. The suggested improvements should be able to measure and verify efficiency of design choices for construction processes of both new and existing buildings. The activity described in this deliverable is part of the documents discussed by regulators working groups. The consequent actions of this task are identified and described in the next sub-chapters as two distinct but interlinked efforts for standardization. Feedbacks of discussion on standardization tables will be reported in D9.7.

## 6.1 Action towards CEN TC 442

Standardization for other sectors (see ISO 15926) and recent efforts of AEC standards (see ISO 12006-2 and Work Item of TC 442) confirm the growing trend of interest for Linked Data applications for information exchange. BIM4EEB aims at participating to these standardization processes through (1) the development of a framework for ontologies in the renovation sector and (2) the test of such technologies in real environment.

After a wide discussion at the various working tables, having identified the need to better standardize the information structure currently available (the result of various ISO and CEN standards but not entirely harmonized), last September 2019 the TC 442 of the CEN did circulate a first draft document specifically dedicated to the topics of ontologies and semantics in the AEC sector: "Building Information Modelling (BIM), Semantic Modelling and Linking Standard (SMLS) for data integration (delivery & sharing) in the built environment". The text, therefore, almost assumes the function of a logical reorganization document, of the standards existing today, and of an innovative proposal, towards their future organic review, in the light of the IT developments that have occurred in the meantime (ISO-STEP 1994).

Following the dissemination of this deliverable, at CEN, it was decided to vote on the opening of a special dedicated Work Item: WI CEN442-0021. The WI was approved on 30.12.2019 and work will start in the next few months of 2020.

Italy, with its national regulatory body and the commission dedicated to BIM: UNI / CT033 / SC05 "BIM and Digital Information Management in Construction", has decided to vote in favour of the opening of WI 0021.

In particular, UNI, in the vote, indicated Eng. PhD Claudio Mirarchi (member of the Polimi team of BIM4EEB) and requested that, among the documents useful for the discussion of the future working group, the results of the BIM4EEB project are considered (at the level of a paranormative document), especially for all aspects related to the built environment (ontologies and standards in general, as well as BIM authoring software, today are in fact highly unbalanced towards the problems related to new buildings only).

Furthermore, in order to foster dialogue with CEN and strengthen the position of BIM4EEB requests, UNI has decided to introduce the results of the project also in its national WG 01 (SC05 / WG01: UNI 11337-2: 2020 - Ontology and Classification), precisely dedicated to the aspects of ontology, semantics and classification in the AEC sector.

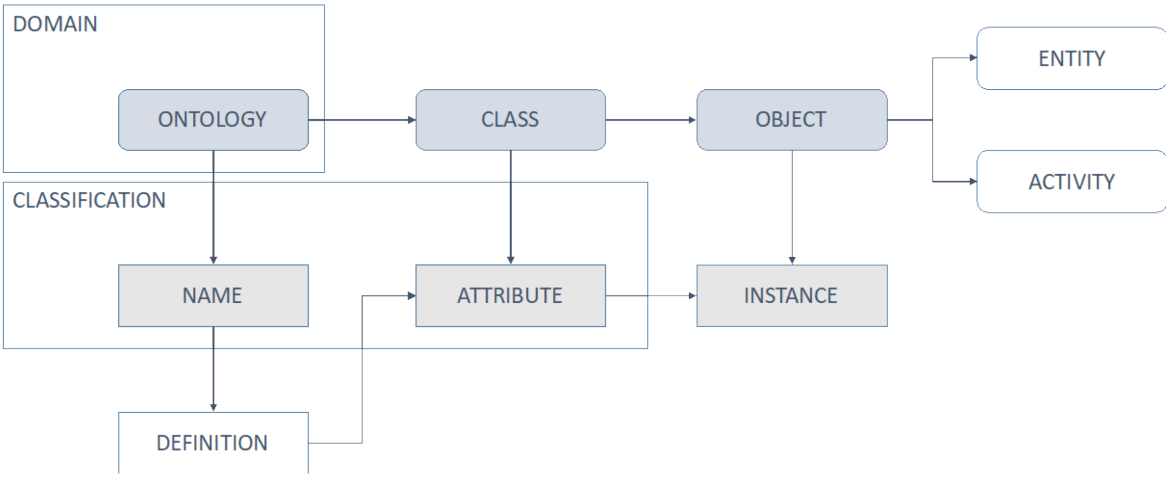


**Figure 23: Example of brainstorming of WG01 UNI approach**

The works of the Italian WG, supported by the results of the BIM4EEB project, will be transferred from Italy to the CEN tables to encourage a community-wide standard on the topics of semantics and linked data, with specific attention to the recovery of built properties.

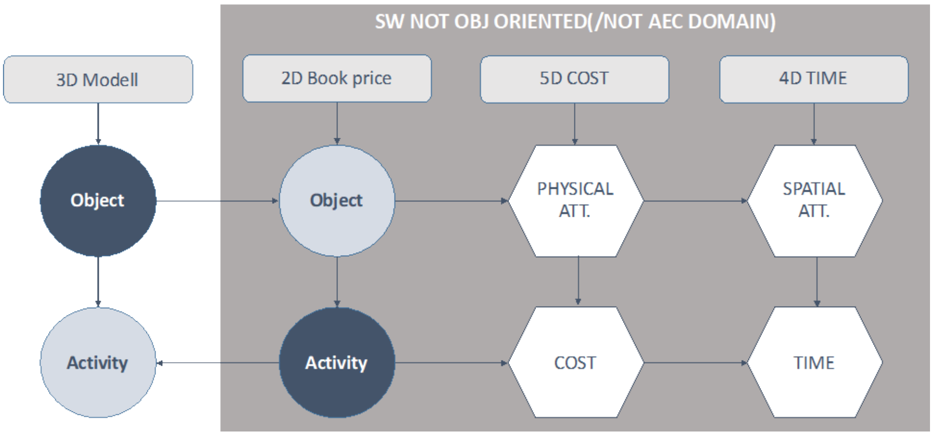


**Figure 24: Example of brainstorming in WG01 UIN – interaction of 3D model data and 2, 4, 5 Dimensions and data**

Considering the results that will be obtained at CEN, UNI will be the promoter of extending the work of BIM4EEB and CENWI4420021 also in ISO, according to a procedure already consolidated within the international regulatory system on BIM.

## 6.2 Action towards Linked Building Data Community Group (W3C)

By the same way, the outputs of WP3 will be discussed also by the Linked Building Data Community Group to enhance the existing framework of ontologies built for the AEC sector.

In particular, the work of ontology alignment and the ontology development of Tasks 3.4 and 3.6 will be object of discussion for this group, where the work is already ahead of CEN and standards.

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