Integration of building product data with BIM modelling: a semantic-based product catalogue and rule checking system

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TESI DOCTORAL

Títol	**Integration of building product data with BIM modelling: a semantic-based product catalogue and rule checking system**
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Catalan abstract

En la indústria AEC (Arquitectura, Enginyeria, Construcció), és cada vegada més necessari automatitzar l'intercanvi d'informació en els processos en els quals intervé la tecnologia BIM (Building Information Modelling). Els experts que participen en aquests processos (arquitectes, enginyers, constructors, etc.) utilitzen diferents tipus d'aplicacions per dur a terme tasques específiques d'acord al seu àmbit de coneixement i la seva responsabilitat. Tot i que cada una d'aquestes aplicacions, separadament, compleix la seva funció, la interoperabilitat entre elles segueix sent un problema a resoldre. En aquests processos es requereix, a més, accedir a dades de fonts diverses i diferents formats, per integrar-los i fer-los accessibles a les aplicacions BIM. En aquesta tesi s'investiguen les dificultats subjacents en aquests dos problemes –la interoperabilitat entre aplicacions i la integració d'informació de múltiple fonts i formats en el context dels processos basats en tecnologies BIM– i es proposen solucions per superar-les.

En primer lloc s'han examinat les ineficiències que actualment existeixen en l'intercanvi d'informació entre sistemes i aplicacions utilitzats en projectes AEC que empren la tecnologia BIM. Un cop identificades, es planteja la seva superació a través de l'aplicació de tecnologies de la Web Semàntica. Per a això, s'analitza la capacitat d'aquestes tecnologies per a integrar dades heterogènies de diferents fonts i àmbits mitjançant ontologies. Finalment, es considera la seva aplicació en el desenvolupament de projectes AEC. A partir d'aquest estudi previ, s'ha pogut concloure que les solucions per millorar la interoperabilitat entre BIM i altres aplicacions a partir de les tecnologies semàntiques estan lluny de proporcionar una solució definitiva al problema de la interoperabilitat.

Per tal de proposar solucions basades en la Web Semàntica per a la integració de dades en processos en què intervenen les tecnologies BIM, s'ha acotat la investigació a un cas d'estudi: la creació d'un catàleg de components prefabricats de formigó amb tecnologies de la Web Semàntica i compatible amb la tecnologia BIM. En el context d'aquest cas d'estudi s'han desenvolupat mètodes i eines per a: 1) integrar dades de components i productes constructius en un catàleg amb contingut semàntic accessible a aplicacions BIM, i 2) aplicar regles d'inferència semàntica per examinar els components inclosos en un model BIM i proporcionar productes compatibles extrets del catàleg. La viabilitat dels mètodes i eines s'ha demostrat en un cas d'aplicació: pre-dimensionat d'elements constructius que compleixen les normatives de seguretat estructural i recerca automatitzada de components alternatius en el catàleg.

Tot i demostrar el benefici potencial de les tecnologies de la Web Semàntica per millorar els processos BIM integrant dades externes, encara hi ha alguns reptes a superar, entre ells, l'escassetat de dades en format RDF i la dificultat en mantenir els enllaços entre dades quan aquests canvien. Els resultats obtinguts en aquesta investigació podrien continuar desenvolupant-se en dues direccions: 1) ampliant el catàleg a nous productes i incorporant noves fonts de dades relacionades amb els mateixos i 2) creant eines que facilitin la creació i el manteniment de regles d'inferència.

Spanish abstract

En la industria AEC (Arquitectura, Ingeniería, Construcción), es cada vez más necesario automatizar el intercambio de información en los procesos en los que interviene la tecnología BIM (Building Information Modelling). Los expertos que participan en estos procesos (arquitectos, ingenieros, constructores, etc.) utilizan diferentes tipos de aplicaciones para llevar a cabo tareas específicas de acuerdo a su ámbito de conocimiento y su responsabilidad. Aunque cada una de estas aplicaciones, separadamente, cumple su función, la interoperabilidad entre ellas sigue siendo un problema a resolver. En estos procesos se requiere acceder a datos de fuentes diversas y distintos formatos, para integrarlos y hacerlos accesibles a las aplicaciones BIM. En esta tesis se investigan las dificultades que subyacen en estos dos ámbitos –la interoperabilidad entre aplicaciones y la integración de información de múltiple fuentes y formatos en el contexto de los procesos basados en tecnologías BIM– y se proponen soluciones para superarlas.

En primer lugar, se han examinado las ineficiencias que actualmente existen en el intercambio de información entre sistemas y aplicaciones utilizados en proyectos AEC que emplean la tecnología BIM. Una vez identificadas, se plantea su superación a través de la aplicación de tecnologías de la Web Semántica. Para ello, se analiza la capacidad de estas tecnologías para integrar datos heterogéneos de diferentes fuentes y ámbitos mediante ontologías. Finalmente, se considera su aplicación en el desarrollo de proyectos AEC. A partir de este estudio previo, se ha podido concluir que las soluciones para mejorar la interoperabilidad entre BIM y otras aplicaciones a partir de las tecnologías semánticas están lejos de proporcionar una solución definitiva al problema de la interoperabilidad.

Con el fin de proponer soluciones basadas en la Web Semántica para la integración de datos en procesos en los que intervienen las tecnologías BIM, se ha acotado la investigación a un caso de estudio: la creación de un catálogo de componentes prefabricados de hormigón con tecnologías de la Web Semántica y compatible con la tecnología BIM. En el contexto de este caso de estudio se han desarrollado métodos y herramientas para: 1) integrar datos de componentes y productos constructivos en un catálogo con contenido semántico accesible a aplicaciones BIM, y 2) aplicar reglas de inferencia semántica para examinar los componentes incluidos en un modelo BIM y proporcionar productos compatibles extraídos del catálogo. La viabilidad de los métodos y herramientas se ha demostrado en un caso de aplicación: pre-dimensionado de elementos constructivos que cumplen las normativas de seguridad estructural y búsqueda automatizada de componentes alternativos en el catálogo.

A pesar de demostrar el beneficio potencial de las tecnologías de la Web Semántica para mejorar los procesos BIM integrando datos externos, todavía hay algunos retos a superar, entre ellos, la escasez de datos en formato RDF y la dificultad en mantener los enlaces entre datos cuando estos cambian. Los resultados obtenidos en esta investigación podrían continuar desarrollándose en dos direcciones: 1) ampliando el catálogo a nuevos productos e incorporando nuevas fuentes de datos relacionadas con los mismos y 2) creando herramientas que faciliten la creación y el mantenimiento de reglas de inferencia.

English abstract

In the AEC industry (Architecture, Engineering, Construction), it is increasingly necessary to automate the exchange of information in processes involving BIM (Building Information Modelling) technology. The experts involved in these processes (architects, engineers, builders, etc.) use different types of applications to carry out specific tasks according to their scope of knowledge and their responsibility. Although each of these applications separately fulfils its function, interoperability between them remains a problem to be solved. In these processes it is also necessary to access data from different sources and different formats to integrate them and make them accessible to BIM applications. This research investigates the difficulties that underlie these two problems – interoperability between applications and the integration of information in the context of processes based on BIM technologies – and propose solutions to overcome them.

In the first place, the inefficiencies that currently exist in the exchange of information between systems and applications used in AEC projects using BIM technology have been examined. Once identified, our objective has been to overcome them through the application of Semantic Web technologies. To do this, the ability of these technologies to integrate heterogeneous data from different sources and domains using ontologies is analysed. Finally, we considered their application in the development of AEC projects. From this previous study, it has been concluded that developed solutions to improve interoperability between BIM and other applications using semantic technologies are still far from providing a definitive solution to the problem of interoperability.

In order to propose solutions based on the Semantic Web for the integration of data in processes involving BIM technologies, the research has been limited to a case study: the creation of a catalogue of precast concrete components with semantic technologies which are compatible with BIM technology. In the context of this case study, we have developed methods and tools to (1) integrate data on components and constructive products in a catalogue with semantic content compatible with BIM technology, and (2) apply the rules of semantic inference to examine the components used on a BIM model and provide compatible products extracted from the catalogue. The feasibility of the methods and tools has been demonstrated in an application case: pre-dimensioned structural elements that comply with structural safety regulations and the automated search of alternative components in the catalogue.

Despite demonstrating the potential of Semantic Web technologies to improve BIM processes by integrating external data, there are still some challenges to overcome, including the shortage of data in RDF format and the difficulty in the maintenance of the links between the data when they change. The results obtained in this research could continue to be developed in two directions (1) expanding the catalogue to new products and integrating new data sources related to them and (2) creating tools that facilitate the creation and maintenance of inference rules.

Table of contents

List of figures

List of listings

List of acronyms

A

AEC	Architecture, Engineering and Construction
AIA	American Institute of Architects
AMF	Asset Management Framework
API	Application Programming Interface

B

BCF	BIM Collaboration Format
bcXML	Building and Construction eXtensible mark-up Language
BDS	Building Description System
BEP	BIM Execution Plan
BEP	Building Energy Performance
BIM	Building Information Modelling
BLIS	Building Lifecycle Interoperability Consortium
BPEP	BIM Project Execution Plan
BRep	Boundary Representation
bSDD	buildingSMART Data Dictionary

C

CAD	Computer-Aided Design
CityGML	City Geography Markup Language
CMAR	Construction Management At Risk
COBie	Construction Operations Building information exchange
CSG	Constructive Solid Geometry

D

D2RQ	Database to RDF Query
DB	Design-Build
DBB	Design-Bid-Build
DL	Description Logic
DTV	Design Transfer View
DXF	Drawing eXchange Format

E

EIF	European Interoperability Framework
ETL	Extract, Transform and Load
ETSI	European Telecommunication Standards Institute

EUPPD	European Union Public Procurement Directive

G

GIS	Geographic Information System

H

HVAC	Heating, Ventilation and Air Conditioning

I

IAI	International Alliance for Interoperability
ICT	Information and Communication Technologies
IDM	Information Delivery Manual
IFC	Industry Foundation Classes
IFD	International Framework for Dictionaries
IPD	Integrated Project Delivery
ISO	International Standards Organisation

J

JSON	JavaScript Object Notation

K

KRS	Knowledge Representation Systems

L

LD	Linked Data
LOD	Level Of Detail
LOD	Level Of Development
LOD	Linked Open Data
LOI	Level of Information

M

MEP	Mechanical, Electrical and Plumbing
MVD	Model View Definition

N

N3	Notation 3
N3Logic	Notation 3 Logic
NLP	Natural Language Processing

O

OBDA	Ontology-Based Data Access
OWL	Web Ontology Language

P

PAS	Publicly Available Specifications
PDT	Product Data Templates
PLC	Product Life Cycle
PSRL	Semantic Web Rule Language

R

R2RML	RDB to RDF Mapping Language
RDF	Resource Description Framework
RDFa	Resource Description Framework in Attributes
RDFS	RDF Schema
RIF	Rule Interchange Format
RV	Reference View

S

SKOS	Simple Knowledge Organization System
SOAP	Simple Object Access Protocol
SPARQL	Simple Protocol and RDF Query Language
STEP	Standard for the Exchange of Product Model Data
SPF	STEP Physical File
SWRL	Semantic Web Rule Language

U

URI	Unique Resource Identifier

W

W3C	World Wide Web Consortium
WWW	World Wide Web

X

XML	eXtensible Markup Language
XSD	XML Schema Definition

1

Introduction

1.1. Overview

This thesis is framed within the ongoing efforts to provide a more efficient and participatory collaboration in the architecture, engineering and construction (AEC) industry.

In today's AEC industry, a large number of software applications (platforms, tools, services, etc.) have been created to support the design, construction and maintenance of buildings. These applications have succeeded in providing better designs and detailed representations of a building, for example, by supporting 3D parametric modelling. However, they are currently providing this support in isolation from each other, without supporting, for example, an appropriate data exchange with other applications.

To facilitate efficient collaboration between agents of AEC industry, it is important to provide the necessary mechanisms to support data exchange. This is often a critical issue, particularly in the development of building projects, where different actors must collaborate over a limited period of time in the design and construction (or retrofitting) of a building. In this collaboration, the actors require some information from others as input to carry out their tasks, especially at the design stage. For example, information about the architectural design is needed to perform the structural design. To facilitate this data exchange, information needs to be transferred using a compatible mechanism (e.g., data exchange formats). The successful transfer of physical data between applications is as important as making its content understandable to the agent to whom it is addressed. Poor communication between agents in aspects such as design intent or those requirements that must be frequently taken into account in the design (design criteria, regulations, etc.) may lead to its remodelling and, consequently, to an inefficient development.

Data exchange between software applications in the AEC industry became more complex in building projects with the advent of the Building Information Model/Modelling (BIM), a methodology aimed at improving productivity and quality in workflows by reducing downtime and costs. The exchange of information about BIM models can be performed using open standards for interoperability. Here, Industry Foundation Classes (IFC) is the most commonly used data model by the industry. However, although this standard includes a wide range of concepts and notions to represent information about a building design, the reality is that practitioners – and more particularly, BIM users – have to deal with various obstacles when they need to exchange information. Some of these problems are already known: information needs to be remodelled, some information is lost in the exchange, there is a lack of rules and restrictions in the propagation of changes, and so forth. Another limitation in the use of standards such as IFC arises when an agent requires information from different sources at a time to carry out a specific task in a project. All these problems fall within the realm of interoperability, which can be described as the ability of software applications to work with other systems to communicate, exchange and use the information. The main difficulty in achieving the desired interoperability between BIM software applications lies in the heterogeneity existing between the different representations of BIM models. These representations are subject to the data structures implemented in each software.

In addition to the limitations on interoperability, mechanisms to facilitate an automated interpretation and processing of the information exchanged between applications also currently remain without adequate support. In recent years, the research community has made substantial efforts to investigate methods to address both issues. Most of the research has been focused on the field of knowledge representation systems (KRS) and methods based on the application of Semantic Web technologies, considering their capabilities to provide: (1) an explicit and unambiguous definition of information and (2) mechanisms to facilitate its automated interpretation by machines. However, although the application of Semantic Web technologies has proven to be viable in different application scenarios, the extent to which they can improve information exchange in the development of BIM-based projects, or even address the interoperability challenge, remains unclear.

1.2. Motivation

Two decades ago, most manufacturing industries around the world shifted from being stand-alone and isolated towards distributed and networked digital systems in their work processes. This paradigm shift seems to be finally appearing in the construction sector as well. Although this sector has historically been characterized as being highly resistant to change, the expectations to develop more efficient design and construction processes throughout the building lifecycle using BIM, are currently high in the sector. However, the idea of a common BIM free of interoperability problems is still far from being a reality. The fundamental problem lies in the diversity of information systems implemented in the BIM applications, which respond to specific design methods and rules.

Some of the problems in data exchange can be found in the way in which the collaboration between industry players is established. In this sense, the construction sector differs from other manufacturing industries in several respects. For example, different teams are created each time a new product – a building project, single and unique – is produced. Furthermore, each project is designed and constructed according to different criteria and in a different place. Suppliers and manufacturers of building materials and components are often constrained by the building location.

Today, practitioners involved in building projects use the Internet to search and exchange different kinds of information necessary to carry out their task more efficiently. In response to the growing demand for accessing and exchanging BIM content over the Internet, software development for the AEC industry is increasingly expanding its capabilities towards this medium, directly or through some kind of middleware (services, plugins and other ICT solutions), created by third parties, opening up opportunities to develop new working processes. These new capacities have led to the initiation of a research line over the last few years to explore the opportunities for BIM developments more connected to Web resources, for example, by creating links between BIM models and the information about product components available in Internet.

Information about components and products is necessary for the development of a building project. However, information requirements about building components and products may be different depending on the agent, the discipline and the stage of the building life cycle in which it is required. Even if this information can be obtained through Web resources, the integration of product information and BIM models remains an unsolved issue. In order to integrate both, there are two difficulties to overcome:

1. Lack of data required by the project. Architects, builders and owners often realise that on-line information about components and products they need for their designs and building models is not easily available, either because it does not exist, it is not easily accessible or it represents a great effort for the manufacturer to facilitate it.
2. Compliance of the available data with the project requirements. The products needed for a specific project need to meet specific requirements (e.g. building regulations, cost limitations, etc.). Currently, there are no search mechanisms which enable the retrieval of on-line product information needs taking into account the project constraints.

In the AEC industry, information about building components and products is provided in various formats, structured according to a diversity of schemes and stored in several support systems. As a result, information systems and interoperability standards used in the development of projects are not capable of providing adequate support to access and efficiently reuse these data. In other fields, for example in Medicine and Health-care, the application of methods based on Semantic Web technologies and the use of ontologies has proven to be successful in providing uniform access to heterogeneous data (Kolias, Stoitsis, Golemati, & Nikita, 2014). The research carried out in this thesis is motivated by the goal of applying methods based on Semantic Web technologies to help overcome the difficulties with data availability and data compliance. The ultimate purpose is not so much to develop new techniques, but rather to exploit the capacities of the existing ones to solve these problems.

It is expected that the findings of this research will help to make professionals of the AEC industry more aware of the potential advantages in providing information about building components in semantic formats, and will suggest directions to integrate Semantic Web technologies in the future development of BIM.

1.3. Research questions and outcomes

In this section we introduce the research questions addressed in this thesis, discuss how they are related to each other, and describe how they are connected with the context of each area investigated and the outcomes obtained.

1.3.1. Semantic Web Technologies to address interoperability problems

The exploration of methods based on Semantic Web technologies to address the need to automate the exchange, integration and interpretation of information in the AEC industry leads to the first *research question* (RQ) in this thesis:

RQ1. Can Semantic Web technologies be applied to provide long-term solutions to the pervading interoperability problems derived from the application of BIM in the AEC industry?

To address this question, in Chapter 2 we start by exploring the inefficiencies that arise in data exchange. These inefficiencies are analysed in four areas: collaboration in the AEC industry (Section 2.1), the Building Information Model/Modelling (Section 2.2), interoperability (Section 2.3) and the use of standards and technologies (Section 2.4). After identifying the problems that lead to these inefficiencies, we focus on investigating their relation to the lack of adequate technological support for interoperability and what alternatives may be considered. This lack of support is also examined in relation to the use of information which is not generated in the design process but rather already available (product catalogues, regulations, geography, climate and urban data, etc.) and which is necessary for the project development. At this point, more research is needed on methods to facilitate an automated integration, interpretation and processing of this external information.

Today, architects, designers and other agents of the AEC industry use the Internet mainly as a means to communicate with each other (e.g., through e-mail, instant messaging and other communication systems); to access different kinds of content (e.g., product catalogues, repositories of BIM components, building regulations, administrative instructions and other related documents available on the websites of public administrations); and to exchange information about building projects (e.g., by using common data environments and sharing files in the cloud). This penetration of the Internet in the industry is leading software developers to integrate new connectivity capabilities and functionalities into BIM applications to support these activities.

In the development of BIM-based projects, access to external contents is often provided through closed software services, where third parties (e.g., independent software developers) do not have direct access to their sources. This service model makes it difficult to provide answers to the broad spectrum of needs that arise in the process of creating a BIM model. An alternative to this service model is the open data approach to create ecosystems, separating the role of data owners and providers from those who will exploit them.

However, accessing and reusing information in projects pose multiple challenges: information is provided in diverse formats, most of which are not intended to facilitate automated processing; it is structured according to different schemes; it is stored in several support systems; and available on many websites. The application of Semantic Web technologies and the use of ontologies, both introduced in Chapter 3, can help face these challenges. Their combination in methods for integrating heterogeneous, scattered and distributed data in a specific domain can facilitate greater support to overcome the current needs of BIM modelling.

1.3.2. The case of building components and products

Most information about building products available on the Web aims at the commercialization of products. For example, different models of building components for BIM are available in online catalogues (BIM Object[1], BIM Components[2], Bimetica[3] and others), including models of components in parametric formats. However, most of these models come only in proprietary formats (e.g., Revit), so they can only be used in the BIM authoring tool for which they have been created. Although this is advantageous for an effective reuse of these models by a specific tool, the models cannot be reused in other BIM software, and in some cases even in different versions of the same tool.

Apart from facilitating the reuse of component models for the creation of BIM models, support is required in projects to reduce the intensive work of collecting data about building components and products. Decision-making about the choice of products, which of them meet certain specifications, or provide information for their calculation, are some examples of project tasks that may require data from different sources. The way in which these data should be provided and integrated to facilitate these tasks leads to the following two connected research questions:

RQ2. Can manufacturers be involved in defining information about their products in Semantic Web formats? If so, in which ways and to obtain what benefits?

RQ3. Can product information be integrated with other related data sources to meet the needs of potential areas of application in the design and construction of buildings?

These two questions are part of a second line of research aimed at exploring methods for the standardization of information about building components and products, addressed in Chapter 4. To answer the first question, we examine the role of manufacturers during the development of building projects. The adoption of BIM in these projects allows agents involved (e.g., architects, designers, engineers, constructors, even owners) to work with more accurate information. However, product manufacturers are generally not involved in this collaboration through BIM. This lack of involvement sometimes makes it difficult to resolve some issues concerning, for example, the choice of products depending on the regulations, the compatibility of products with others, their installation, or the

[1] BIM Object, http://www.bimobject.com/.
[2] BIM components, https://bimcomponents.com/.
[3] Bimetica, http://bimetica.com/.

implications for their future maintenance. To address these issues, methods to capture this knowledge and to transform it into information that can be shared and used effectively in the projects seem to be missing.

The second question leads us to examine how information about products and components can be combined with other related data sources using the Semantic Web technologies (Section 4.3). Here, different methods are explored based on the linked data approach and ETL (Extract, Transform and Load) processes. The ultimate aim of this data integration is to facilitate the access, processing and interpretation of this information to facilitate greater support of information about building products in BIM-based projects.

1.3.3. Component checking and product suggestion: information reuse

As Semantic Web technologies can be used to represent information about building components and products in a way that can be related to BIM data and other external data, the last part of this thesis investigates the possibility of suggesting building materials or components found in the Web during the process of modelling a building with BIM software to the end user. This leads to our fourth research question:

RQ4. Can the Semantic Web technologies be applied to improve the process of building design and modelling by suggesting building components and products for a specific project to the design team?

In addressing this question, we focus particularly on inference and semantic reasoning engines which are supported by Semantic Web technologies. Particularly, our concern is to know if these technologies can be applied for semantic rule-checking with the purpose of suggesting building components that meet the requirements of a project being modelled with BIM. To demonstrate this possibility, we have put together a process which encompasses five steps (Figure 1.1):

1) Transforming information about building products, defined by manufacturers, into Semantic Web formats. This step is necessary to facilitate its integration with other data sources (Chapter 4).
2) Integrating different data from distributed and heterogeneous sources (e.g., product information from different manufacturers, classification systems, etc.) in order to respond to the needs of a particular application domain (Chapter 4).
3) Facilitating the development of services implemented using these technologies, which can be created by third parties, in this case with the aim of assisting architects and designers in choosing suitable components and products during the building modelling process (Chapter 4 and 5).
4) Extracting partial representations of the BIM models defined through Semantic Web languages (Chapter 5).
5) Checking the components of BIM models using inference rules described through languages compatible with Semantic Web languages, and inference engines able to process them (Chapter 5).

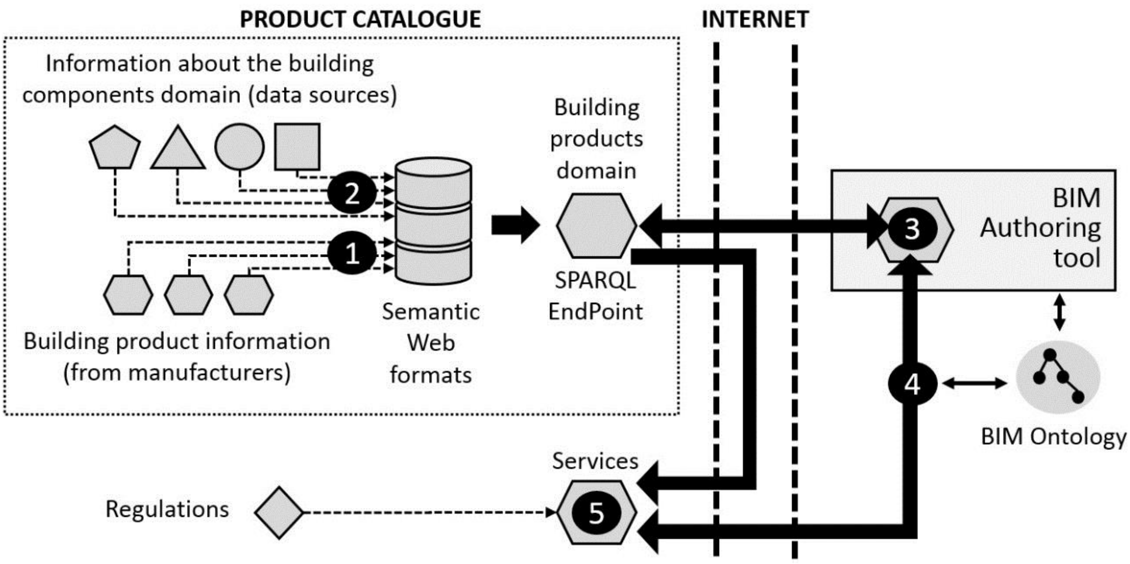

Figure 1.1: Diagram showing the five steps of the process – from the definition and integration of the information into the catalogue to its use in services to assist end-users in the development of BIM models.

The two first steps (1 and 2) were conducted in the context of the BAUKOM research project whose goal was to create a catalogue of precast concrete components. The catalogue contains information about products as defined by manufacturers integrated with other data sources (e.g., classification systems and building codes). The combined information is stored in RDF and is accessible as linked data through a SPARQL endpoint service. The SPARQL language enables end-users to retrieve information and get answers to complex questions through flexible querying. Even simpler intermediary interfaces and languages (e.g., JSON) are available to facilitate this querying process. SPARQL queries can be encapsulated in services which automatically interpret information. These services can be implemented as stand-alone applications, Web services and plug-ins for BIM authoring tools.

For the two last steps (four and five), a method is implemented to demonstrate how information extracted from a BIM model, provided in the RDF format, can be checked against particular regulations described in the rule languages designed for the Semantic Web. On the one hand, methods are investigated to carry out this extraction through ontological representations of the data structure of BIM authoring tools. On the other hand, a method is proposed for the creation and use of semantic inference rules to check BIM models and provide suggestions about alternative products. The method is applied in a rule-checking and suggestion system that involves three data sources: (1) a BIM model, (2) a catalogue of products, and (3) building regulations. A proof of concept of this system is implemented as a software service to demonstrate its use to evaluate the components of a BIM model in terms of structural safety requirements, and to provide suggestions derived from to the product catalogue.

1.4. Methodology

The four research questions introduced in the previous section are addressed by undertaking a comprehensive investigation which encompasses various areas: artificial intelligence, knowledge-based systems, and modern methods of conceptual modelling and information systems. The investigation has focused on techniques used to partially automate the integration of disparate, heterogeneous data sources, and to conduct the subsequent reasoning. For this purpose, data integration methods based on Semantic Web technologies have proven to be effective in capturing and transforming information from different data sources according to a domain ontology. In these methods, ontologies are the backbone "for the management of formalized knowledge in the context of distributed systems" (Ding, van Rijsbergen, Ounis, & Jose, 2003).

In response to the first research question above about whether Semantic Web technologies can be applied to provide solutions to overcome the interoperability problems between BIM applications, methods are investigated to integrate data from the BIM model with other data sources. This integration is possible using ontologies as a means to homogenize the structural and semantic heterogeneity of the data from different sources that need to be integrated according to the conceptual representation of a domain of interest. The application of these methods for the purpose outlined above is investigated through a review of literature, examples of research projects developed in recent years, and based on experience gained through several collaborations in research projects.

To address the second and third questions of this research, which are related to the use of Semantic Web technologies to provide greater support to the access, combination and interpretation of information defined externally to projects (e.g., product catalogues, repositories of BIM components, and building codes and regulations), we delimit our research to the domain of building components and products. After analysing the shortcomings and limitations of the current product catalogues on the Web, methods which enable manufacturers to define the information of their products through a set of interfaces have been examined. Following this, methods to transform and integrate the information about products facilitated by manufacturers with information from other data sources related to this domain are analysed.

The last research question concerns the application of inference rules. Various rule languages and compatible reasoning engines which can be used to enhance BIM modelling are studied. These semantic rules can be useful for checking the consistency between building components and BIM models. In particular, the compliance of the BIM model components with the building regulations is addressed. As a result, a semantic rule-checking system has been created to check whether the components of a BIM model comply with the building regulations.

The relations between the four research questions, the corresponding research lines and their application in the case study are illustrated in Figure 1.2.

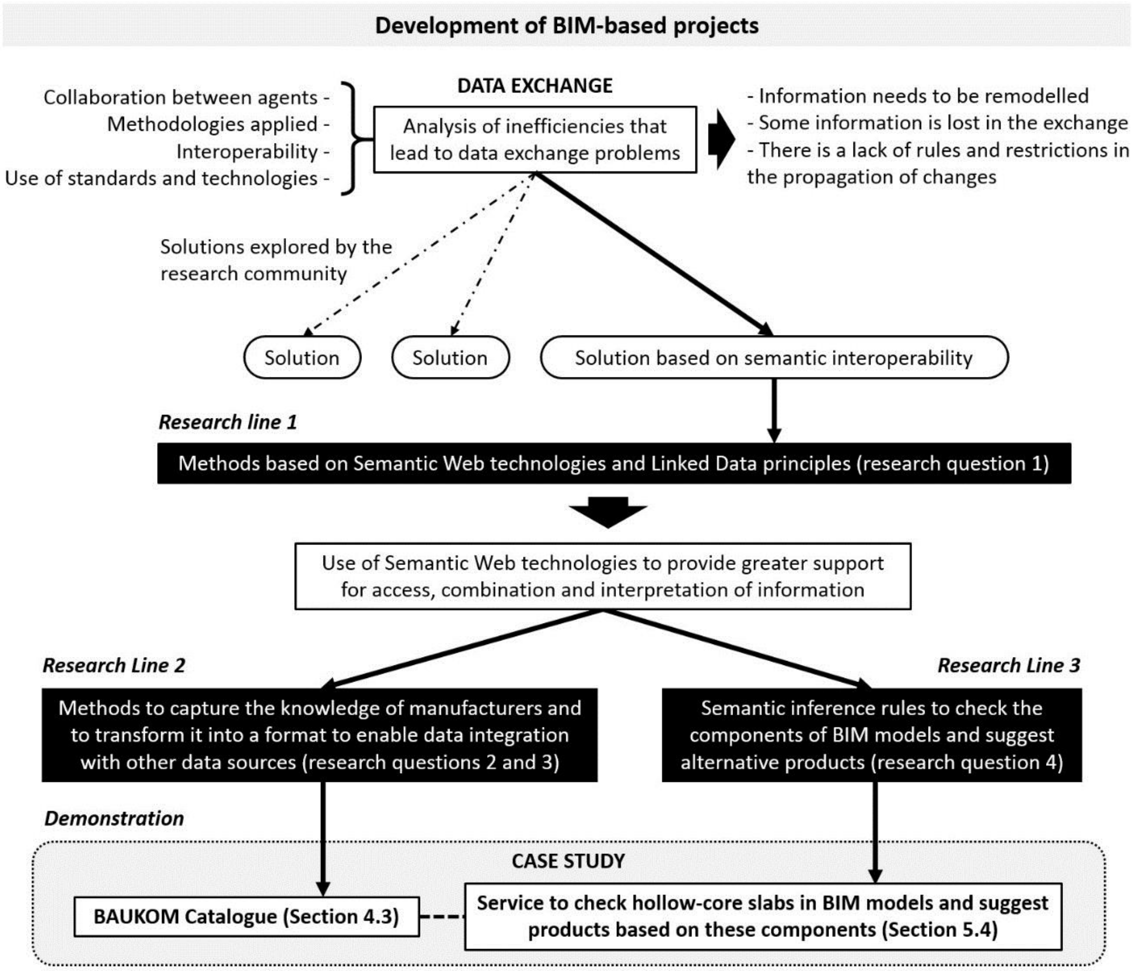

Figure 1.2: Relation between the research questions, the corresponding research lines and their application in the case study.

1.5. Hypotheses

The research which has been conducted is based on the following connected hypotheses:

1. Need for a common base for describing products. The use of the same basis to describe building components and product features through parametric data models can ease the linking and integration of their data with the data from other related domains when they are all described using the Semantic Web languages.
2. Reuse of information. There can be a greater reuse of information that can be generated outside the context of building projects and is not specific to the tools used for their development. For example, information about building products, prices, assembly compatibilities, regulations, product specifications and, in general, any information that could be useful for the development of a BIM, can be provided by standardizing data models using ontologies.
3. Support for intelligent processing. The capabilities of Semantic Web technologies and the linked data principles to interconnect structured data from different sources at the data level, facilitate their reuse by transforming the implicit knowledge into explicit knowledge through reasoning techniques.
4. Automating the checking process. Regulations affecting building design and construction can be described in the form of rules through languages that enable their processing in combination with BIM data defined in Semantic Web languages. The flexibility in this combination makes the checking of BIM models against regulations more dynamic and standardized.

1.6. Outline of the thesis

The rest of this document is structured in the following chapters:

- **Chapter 2 – Use and exchange of information in BIM projects**, provides a comprehensive introduction to the main topics and concepts which make the framework of this research. The chapter gives an overview of the difficulties that currently exist for collaboration between the actors involved in the development of work processes in different stages of the life cycle of a building. These difficulties are investigated based on the analysis of the barriers, limitations and shortcomings that come up when they (actors) need to exchange information related to the building (e.g., designs, costs, schedules), especially in building projects developed using the BIM methodology with more information to be exchanged.
- **Chapter 3 – Application of Semantic Web technologies to reuse and share building information**, introduces the theoretical foundations on which the Semantic Web technologies and linked data principles are based, and how they can be useful for overcoming some of the inefficiencies in the exchange of information outlined in Chapter 2. The first part of the chapter reviews the fundamental concepts, how these technologies can be applied for knowledge representation of building information, and how they can be applied to provide

data integration from different heterogeneous data sources. The final part of the chapter is a dedicated state-of-the-art review of the application of these technologies in the construction sector.

- **Chapter 4 – Building product information**, introduces the issue of how Semantic Web technologies can be applied to integrate data related to the domain of building components and products in order to facilitate its automatic processing on a semantic level. To address this issue, the first part of this chapter examines the central issues in the use of this information for BIM modelling, the role of manufacturers in providing it, and how knowledge and expertise about their products can be captured to be used in building design. The second part of this chapter includes a review of the most used catalogues and libraries of BIM objects. A brief overview of the state of the research in providing new strategies to facilitate greater interaction and reuse of BIM objects from catalogues is also given. The third part of the chapter examines some methods based on Semantic Web technologies to provide data integration processes implemented in the context of the research project BAUKOM.
- **Chapter 5 – Component checking and product suggestion for the design phases in BIM-based projects using Semantic Web technologies**, aims to demonstrate benefits that can be achieved with the application of Semantic Web technologies. In this part, semantic inference rules are investigated to provide consistent methods to check BIM models and provide suggestions based on alternative products. These methods are investigated to provide solutions to the redesign problems existing between designers and other agents who participate in the design of BIM-based projects. To provide this support, a methodology is presented for the creation and usage of semantic inference rules for checking BIM models and suggesting building products as valid candidates. This methodology is applied in a rule-checking and suggestion system considering three data sources: (1) a BIM model, (2) a catalogue of products, and (3) regulations. The last part of this chapter is dedicated to describing how this methodology was applied in the implementation of a prototype service.
- **Chapter 6 – Conclusions**, reflects on the main results of this thesis. Suggestions on possible directions for future work are also provided.

2

Use and exchange of information in BIM-based projects

This chapter provides a comprehensive introduction to the main topics and concepts that form the framework of the research, focusing on the inefficiencies in the use and exchange of information over the different stages of the building life cycle, and more particularly, those arising in the development of BIM-based projects. These inefficiencies are analysed in four different areas: (1) collaboration between the different actors, (2) application of methodologies, (3) interoperability between software applications, and (4) use of standards and technologies. The inefficiencies in each of these areas are documented in combination with a review of the context where they appear, including real-world examples showing how practitioners are currently dealing with each of them.

2.1. Collaboration in the AEC industry

Today, the AEC industry is demanding new tools and methodologies to be more efficient in the development of the different stages of the building life cycle in order to reduce the costs and errors[4]. Agents of this industry (architects, engineers, owners, consultants, contractors and builders, among others) often have to work collaboratively to carry out the design, construction, operation and maintenance of buildings. To be effective in this collaboration, the agents have to find the right way to communicate to each other during the different work processes, so that the information to be exchanged can be interpreted correctly and seamlessly.

[4] In the National Institute of Standards and Technology (NIST) report (Gallaher et al., 2004), the authors claim that costs in building projects can be reduced by (1) the presence of fewer construction errors that need to be fixed on site, and (2) improving efficiency in the offices when project participants have access (remotely) to the project information they require.

This is difficult to achieve in the current development of building projects because the information provided should also be accompanied by an understanding of it, for example in those aspects related to the overall intention of the design. Moreover, there are many decisions that are made during the development of a project that cannot be anticipated and that modify the requirements of the information to be exchanged. Other conflicts arise, for example in the lack of delimitation of the responsibility that each agent has in its part of the process. For instance, architects and structural engineers share the responsibility in the design of a structural system and need to harmonize their different design criteria.

From a historical perspective, building construction is a multidisciplinary sector where drawings have traditionally been the medium used to exchange information and communicate ideas among the different disciplines. However, the advent of computers and digital technologies has resulted in new forms of collaboration between the agents of this industry. The increasing penetration of ICT in developing new communication and management tools, the production of software applications increasingly capable of managing building design information in real time and the increasing adoption of BIM as a working methodology, are leading the industry towards greater efficiency in the development of design, planning, construction and maintenance stages of buildings. This efficiency is also obtained in reducing costs and increasing productivity and quality, all this through a paradigm shift that increasingly seeks to integrate processes throughout the life cycle (Arayici & Aouad, 2011). However, most project teams still have to struggle to find the right way to communicate with each other (Senescu, Aranda-Mena, & Haymaker, 2013; Thomassen, 2011). The lack of sufficient knowledge of professionals about the technologies and communication tools, and about their proper use, is one of the main obstacles.

It is often claimed that the AEC industry is still far from reaching a level similar to other industries, such as the aerospace and automotive industries, in terms of integration of agents, processes and technologies to support collaboration. One of the difficulties lies in the short-term approach of the partnership typically set up in AEC industry projects (Khalfan, Khan, & Maqsood, 2015). Indeed, project teams are often specifically created for a given project. Team members are selected based on the characteristics of the project (budget, location, etc.).

This section analyses the way in which agents of the industry are currently carrying out this collaboration and how this gives rise to inefficiencies in the use and exchange of information. This question is examined from different perspectives: coordination in building projects, the impact of ICT on coordination and communication, and the integrated practice.

2.1.1. Coordination in building projects

An effective communication[5] between the agents involved in a building project is necessary to ensure the appropriate management of its development and to be successful in its delivery according to the requirements established in the project. Despite the advances in the construction sector in recent decades, for example through the adoption of the BIM methodology, some challenges remain to be overcome. For example, some parts of the industry have difficulties in changing their traditional processes towards new methodologies (Zakaria, Mohamed Ali, Tarmizi Haron, Marshall-Ponting, & Abd Hamid, 2013). One of the main difficulties seems to be in the management of large information flows, which require enormous efforts for coordination (Ali & Rahmat, 2009) during various processes that involve different agents with different skill levels, knowledge and experience, as well as issues related to the particular business interests or mistrust in sharing information.

In order to properly coordinate these information flows, the use of standards, processes and tools designed to facilitate the management of digital information in a consistent way must be aligned with the needs of each building project. In addition, project stakeholders must agree on some basic rules before starting the project regarding what information should be shared, and how, for the common benefit of the whole team (Khanzode & Reed, 2008). Information systems implemented in BIM software (BIM authoring tools, structural calculation programs and so on) play a key role in facilitating this coordination, by capturing and representing expert knowledge in order to facilitate the creation of designs for each discipline, and exchanging these designs (building models) with the other disciplines and parties involved in the project. What is difficult here is making the information about the designs consistent and comprehensible to others who will use them to develop the next part of the project. This requires choosing the appropriate communication systems.

Various ICT tools, some of them available as services and applications on the Web, have emerged recently in order to facilitate the communication between the different actors involved in a project. These tools are reviewed in the following section.

2.1.2. Impact of ICT on coordination and communication between practitioners

The integration of ICT in the AEC industry is contributing to boosting industrialization by making work processes more open and collaborative. Since this is a fragmented industry – mostly comprised of SMEs[6] – where project stakeholders need to work in parallel and from different geographically separated places, the use of ICT is essential to support coordination and collaborative work in these developments. Potential benefits in the use of ICT to improve the overall management of building projects have been widely discussed in the literature by different authors (Li & Wang, 2003; Love, Irani, & Edwards,

[5] The term "communication" in this context refers to the capacity to share some kind of meaning to reach a mutual understanding, as defined in Emmitt and Gorse (2009).

[6] For example, in the United Kingdom over 99% of AEC businesses are SMEs (UK Cabinet Office, 2016).

2005; Peansupap & Walker, 2005; Root & Thorpe, 2001; and others). Among these benefits are: improving communications and global decisions, greater control on management, richer information for decision-making, closer relationships, and faster and more accurate communication flows, among others.

Through a literature review (Böhms, Bonsma, Bourdeau, & Samad, 2009; Onyegiri, Nwachukwu, & Jamike, 2011; Yang, Ahuja, & Shankar, 2007; and others), it can be concluded that there are a lot of companies, organizations and practitioners in most industrialized countries around the world that are aware of the benefits of ICT for project management in the AEC industry. They also recognize the role of ICT as a key factor to support innovative and powerful solutions addressed to more efficiently perform this management.

Recently, many free multi-user tools have emerged aimed at improving the management and planning of project activities (e.g., Trello[7], Podio[8], 4Projects[9] and Basecamp[10]). Most of these tools are accessible from web browsers and applications available for computers, mobile phones and tablets. In addition to the integrated planning capabilities, these tools allow stakeholders to upload information in the form of text, images, screenshots, documents and CAD/BIM files, and to define thematic channels to discuss specific topics. Furthermore, these tools are also compatible and easily connectable to other Internet communication tools (e.g., Slack[11], Flow[12] and Quip[13]). Providing support to carry out all these actions is especially crucial when team members of a project are geographically separated, for example in projects developed at an international level[14].

Figure 2.1 shows an example in which three tools are connected to carry out the design of a building in collaboration. Slack (on the left of Figure 2.1) is used to discuss issues and approaches among project stakeholders. Trello (in the top right of Figure 2.1) is a Web-based project management application that provides an overview of the task's progress, including information about stakeholders and related material. It is based on the Kanban[15] system. Information about Trello can be accessed from Revit (in the bottom right of Figure 2.1). Trello boards and tasks can be easily managed in Revit through a plug-in.

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[7] Trello. Retrieved from https://trello.com/.
[8] Podio. Retrieved from https://podio.com/.
[9] 4Projects. Retrieved from https://n3g.4projects.com/.
[10] Basecamp. Retrieved from https://basecamp.com/.
[11] Slack. Retrieved from https://slack.com/.
[12] Flow. Retrieved from https://www.getflow.com/.
[13] Quip. Retrieved from https://quip.com/solutions/team-project-management/.
[14] Difficulties related to communication and the management of remote projects have been discussed by different authors: Kestle and London (2002), Yang et al. (2007), and Sidawi (2012).
[15] The Kanban system is a scheduling system created by Toyota in 1953.

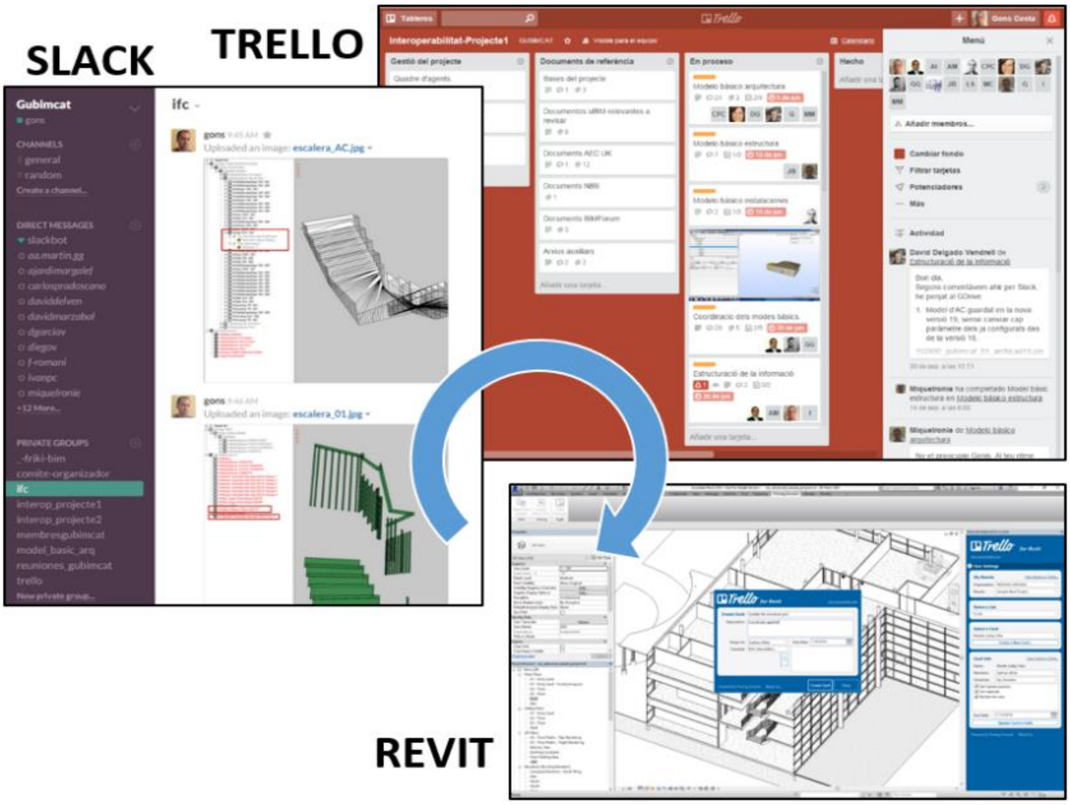

Figure 2.1: Example in which three connected tools, Slack, Trello and Revit, are used during the design of a building.

In conclusion, ICT plays an important role in the efficient development of building projects, not only by facilitating mechanisms for coordination and communication between agents, but also by fostering the exchange of different types of content or physical information about each part of the design.

2.1.3. Integrated Practice

The AEC industry has undergone a major transformation in recent years as a result of the demands of an increasingly competitive market, in which the ability to innovate and adapt is playing a decisive role in the improvement of industrialization of its processes (Eichert & Kazi, 2007). Advances in the development of more powerful applications for building design and modelling, combined with the penetration of ICT in this sector, is leading to new forms of collaboration. However, to obtain a significant impact in this collaboration, interdisciplinary solutions seem more needed than those intended to cover a single stage, discipline or project. The success of this type of solution depends on the capabilities of the technologies. However, this success also involves a change in work habits of all the agents of this industry: promoters, users, architects, engineers, contractors, industrialists and public administrations (Coloma, 2011).

A discipline that arises from the need to work based on this holistic approach is integrated practice. The term “integrated practice” has different meanings in the world. In building construction it refers to the aim of improving the collaboration between professionals involved in the processes of building design and construction. The expected result of its application is a faster, efficient, rational and economic construction of buildings with the aim of satisfying the growing demand of the current industry in terms of sustainability, increased quality and better control of costs and planning. In the book *Integrated Practice in Architecture,* George Elvin (2007) describes the term "Integrated Practice" as "a holistic approach to building in which all project stakeholders and participants work in highly collaborative relationships throughout the complete facility life cycle to achieve effective and efficient buildings". This high level of collaboration requires a comprehensive model of working that allows multiple disciplines to be encompassed where everything is developed in the right time, instead of having separate disciplines that only occasionally work together. Following this idea, Jernigan (2008) states that integrated practice should be subject to five basic principles in order to reach this comprehensive model when starting a project: communication, integration, interoperability, knowledge and certainty.

In order to provide this high level of collaborative relationships, all stakeholders involved in a project should participate in defining its scope. This condition is one of the principles of integrated practice which states that a shared vision of the project may allow stakeholders to plan together an effective way for its development (Elvin, 2007). This participation could also be extended to industrial agents who are not directly involved in a project, for example building product manufacturers.

A more pragmatic approach to integrated practice gave rise to the Integrated Project Delivery (IPD). According to the American Institute of Architects (AIA), IPD is defined as "a project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction" (AIA, 2007). Accordingly, IPD is based on the principles of integrated practice (Calbert, 2013) described by Elvin (2010) as "adaptability, innovation, economy, learning, direct experience, and Continuous Process Improvement (CPI)".

The benefits of applying an IPD process have been represented in a well-known diagram by MacLeamy (Figure 2.2). MacLeamy's Curve (2004) was introduced in the Construction Users Roundtable report "Collaboration, Integrated Information, and the Project Lifecycle in Building Design and Construction and Operation". The curve shows the impact on the distribution of efforts in the traditional design process compared to the integrated practice design process (blue and brown curves). The main differences are in terms of the cost of design changes during all phases of the building project life cycle (white curves).

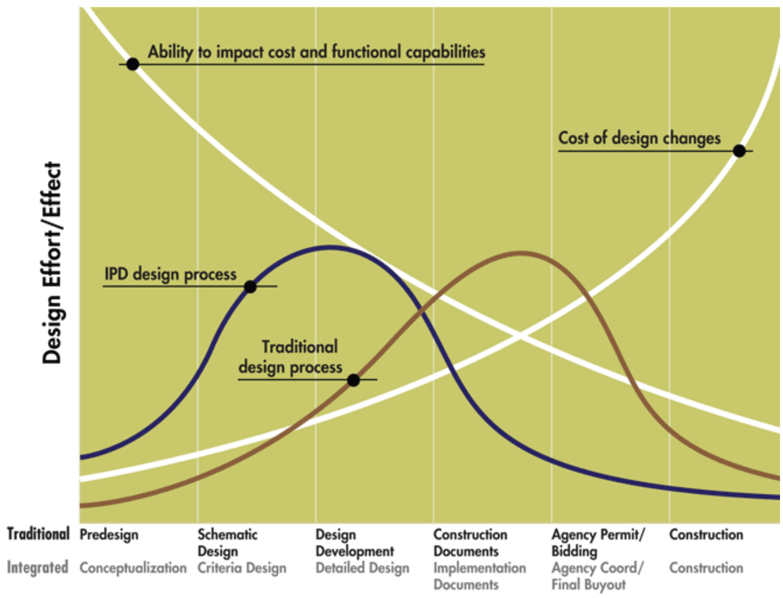

Figure 2.2: MacLeamy's Curve (2004).

To build efficiently, it is necessary for owners and promoters to meet the business goals within specific constraints in terms of (1) budget, (2) schedule and (3) level of quality required to support operations with a predictable and shared risk (AIA, 2007). Because it is difficult to meet these three objectives in the traditional design process, the IPD emerges as a method to optimize them, focusing on the contractual aspect as a means to prioritize project objectives over individual interests. Figure 2.3 shows a comparison between the traditional and integrated design processes provided by the AIA California Council in 2007. The consequences due to the application of IPD depend on the stage of the project development (AIA, 2007).

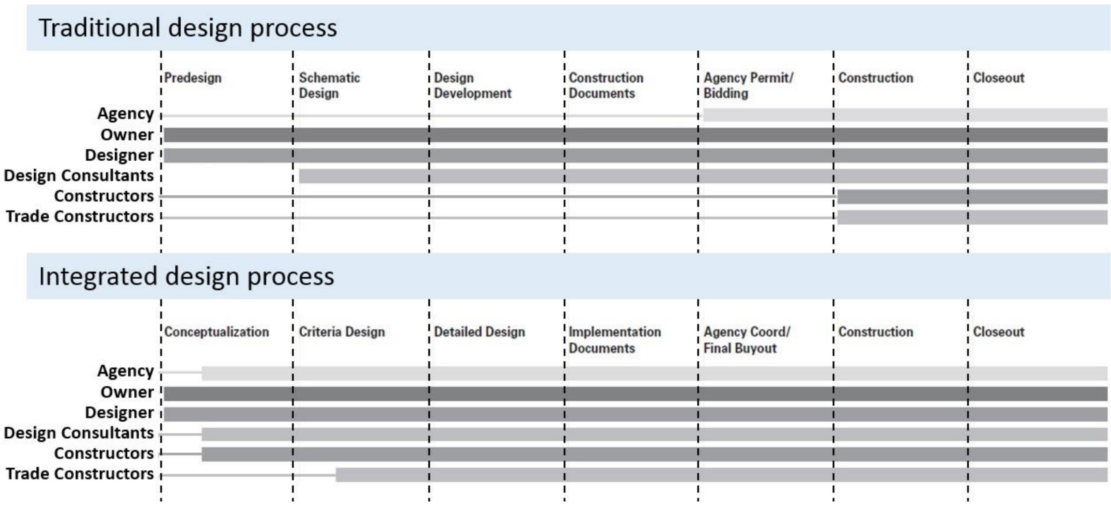

Figure 2.3: Comparison between the traditional and integrated design processes (AIA, 2007).

Despite the advantages of IPD, other delivery methods for the development of building projects may be more appropriate depending on the needs, purposes and reality of the AEC industry today. Delivery methods can be classified in different ways depending on these and other factors such as the culture and the laws in each country. A classification of the most applied includes: Design-Bid-Build (DBB), Construction Management At

Risk (CMAR), Design-Build-Finance-Maintain (DBFM) and Design-Build (DB)[16]. Any of these methods is typically chosen according to the owner's needs to organize and finance the development of the project during its various stages. This is formalized through legal agreements with the agents involved. The main difference between delivery methods lies on the division of responsibilities between project partners.

The considerations in selecting one delivery method may depend on the priorities concerning the risk assessment in terms of the budget, design and schedule, but also on the level of expertise of the owners (CMAA, 2012). The selection of the method, therefore, will determine the way in which the partners will collaborate. In IPD projects, for example, collaboration between the primary actors is defined through a contractual relationship. According to CMAA (2012), the primary actors in an IPD process are the owners, designers and contractors, engineers, who collectively manage liability, risk and responsibility for project delivery through a multi-party contract. Therefore, one of the objectives behind IPD is breaking down the silos of responsibility in building projects (AIA, 2007), sharing risk and reward. This allows players to align their interests and achieve a more optimal development of the project.

It seems more difficult to adopt IPD processes in countries where public procurement in building projects is often subject to separate bidding processes for the design and construction stages. In this case, the actors involved in each stage are different (and not necessarily known beforehand). This also affects the requirements for project delivery where the components and materials specified in the design must be provided as generic solutions in order to avoid conflicts of interest. This approach followed in public procurement also affects the development of private projects due to the influence of regulations and laws.

The search for new methods to reduce the impact on the cost of design changes during the building project life cycle is a topic that has been undergoing for a long time in the AEC industry. For example, in 1976 Boyd Paulson sketched a graph[17] representing how the influence level over the project costs falls as the project evolves during its stages (white line in Figure 2.2). Paulson also pointed out that a good understanding of this influence is vital to provide a common optimization of overall project costs and benefits. This need for greater control of the project costs through its development stages has laid the foundations for bringing the industry towards the use of BIM methodology. However, from an economic perspective, the application of IPD is not necessarily profitable or feasible for all projects. Currently, while potential savings can be made on its application in large and medium-size projects, they are not necessarily achieved in small-size projects.

[16] A more extensive explanation of each of these methods is provided in the book *Integrated Practice in Architecture* (Elvin, 2007) and in the document An owner's guide to project delivery methods (CMAA, 2012).

[17] In the literature, the graph sketched by Paulson in 1976 is referred to as "Paulson's curve".

Another method with similar objectives to those of integrated practice is “lean construction”. Ingle and Waghmare (2015) describe lean construction as a “combination of operational research and practical development in design and construction with an adaption of lean manufacturing principles and practices to the end-to-end design and construction process”. This method emerged in the 1990s with the aim of achieving better management of construction processes by reducing costs, waste of materials, time and efforts to generate the maximum value (Koskela, Ballard, Howell, & Tommelein, 2002). However, an obstacle that appears both for integrated practice and lean construction lies in the initial investment that is required in the design stages to avoid (or anticipate) the cost of design changes (see MacLeamy’s curve, Figure 2.2). Here the problem is twofold. While many owners are still unaware of the benefits of avoiding costs in the design stages, others are not willing to provide the initial additional investment in these stages.

In conclusion, a transformation of the AEC industry towards collaborative forms based on integrated practice involves changes in working methodologies, requiring a redefinition of roles and a period of time to implement changes. This transformation of the industry nowadays seems to be achieved through the adoption of the BIM methodology, which is introduced in the following section.

2.2. Building Information Model/Modelling (BIM)

The idea behind BIM has been around for over 40 years since the first computer systems to aid in architectural design began to appear. However, BIM does not have a single and widely accepted definition. There are many definitions about what BIM is, and also multiple approaches about how it should be applied in the design, construction and maintenance of buildings. For example, in the book *BIM Handbook: A Guide to Building Information Modelling for Owners, Managers, Designers, Engineers and Contractors* (2008), Eastman et al. define BIM as a precise and virtual model of a building built digitally, which, once completed, contains precise geometry and other relevant data needed to support the construction, manufacturing and purchasing activities needed to realize the building.

As a concept, BIM comprises two basic meanings: as a process (e.g., modelling) and as a product (e.g., model). On the one hand, BIM refers to the “processes” of generating and managing building data during its entire life cycle. On the other, it refers to a “digital data model” which encapsulates the graphical, physical and functional characteristics of buildings (Wang & Hamilton, 2009). In the following sections and chapters, the term “building model” will be considered under this definition. Other authors (Fuentes, 2014; Penttilä, 2006; Succar, 2009) also refer to BIM as a methodology intended to enable technical design through a three-dimensional representation of assembled components (columns, beams, walls, stairs, supporting structures, windows, doors, among others). This methodology contrasts in many ways with the traditional methods and work processes in which the information is delivered through 2D CAD formats (Mahdjoubi, Brebbia, & Laing, 2015).

The design of a building through an integrated data model can help to enhance the productivity and quality in the workflows by reducing downtime and costs, especially in the development of highly industrialized projects. Gathering all the information about the building into a single model avoids information being repeated by the different team members involved in the design and construction processes (architects, engineers, consultants and others), who access the BIM model to extract and modify the information they need. This facilitates, for example, the simulation of different features of the building (structural, energy, etc.), a more realistic project planning, an accurate estimation of costs and the resolution of conflicts during the design stage, among other benefits.

From a historical perspective, the potential uses and applications of BIM in the industry have been investigated for decades by various authors through different theories on its practical application. One of the early researchers in this area was Professor Charles M. Eastman from the Georgia Institute of Technology. In his articles “An Outline of the Building Description System” (1974) and “The Use of Computers Instead of Drawings in Building Design” (1975), Eastman introduced a working prototype called the “Building Description System” (BDS) based on four hierarchical levels: topology, geometry, templates and instances. In his words, the system acts as “a design coordinator and analyser, providing a single integrated database for visual and quantitative analyses, for testing spatial conflicts and for drafting” (Eastman, 1975), which is designed to “accommodate a catalogue of such descriptions for standard elements in order to reduce the time spent on element definitions” (Eastman, 1975).

Between the late 1970s and early 1980s the research on the BDS approach evolved into the terms “Building Product Models” (USA) and “Product Information Models” (Europe). These two terms gave rise to the concept of “Building Modelling”, which first appeared in the article “Building Modelling: The Key to Integrated Construction CAD” published by Robert Aish in 1986, which provided a conceptual approach similar to the idea of how the BIM is understood and used today. The concept of BIM was also the focus of the RATAS project initiated in Finland in 1985. The aim of this project was the creation of a roadmap to achieve a more efficient use of information technology in the construction sector (Björk, 2009).

Seven years later, the term “Building Information Model” first appeared in an article published by van Nederveen and Tolman in the journal *Automation in Construction* (1992). However, Eastman (2007) and other authors agree that the person responsible for popularizing the term “BIM” was Jerry Laiserin through his publications: “Comparing pommes and naranjas” (2002) and “The BIM page: Building information modeling – the great debate” (2003). Before this popularization, however, some architectural design tools had already been developed to incorporate the principles of BIM. The first tool considered as such was ArchiCAD. This tool, developed by the Hungarian company Graphisoft in 1987, introduced the concept of virtual building.

Today, BIM is an expanding field of study incorporating many knowledge domains within the AEC industry (Succar, 2009). As a result, it is difficult to provide a detailed definition of BIM since it is constantly evolving. In the same way that many authors have provided different definitions of BIM, others have stated what it is not. For example, Jernigan (2008) stated that “BIM is not about software. It is about how people think about and use technology”. As for its adoption by industry, it seems that BIM is gaining popularity among practitioners and companies in some countries more than in others, so there are different expansion velocities across the world. This variation seems to be due to cultural aspects, laws and regulations, and the maturity or ability of companies to readjust their processes.

2.2.1. Problems and shortcomings

The application of BIM in the AEC industry is leading practitioners to face a whole new set of problems compared to the traditional practice. A large number of documents can be found in the literature that discuss the different problems and complexities related to the application and implementation of BIM methodology. This section focuses on analysing the central issues and those problems that are most related to this research.

Recent surveys (e.g., Costa et al., 2016) carried out in the AEC industry in countries like Spain seem to indicate that many of these problems are related to the lack of preparation of the sector. This inability prevents all the expected benefits in the application of the BIM methodology being received. Lack of maturity can lead to technical and technological problems. An example is when BIM models quickly grow in size, both within applications and when they are exported to a specific format. This can occur for different reasons: inefficient management, ignorance of the export procedure or a lack of partitioning of models that are very large (e.g., football stadiums). Furthermore, models with a large volume of information may pose a problem in terms of being processed by the hardware of regular computers. BIM authoring tools like Revit, for instance, usually consume a lot of RAM memory and CPU processing power. This leads to the requirement of a minimum investment in workstations (Day, 2011).

However, one of the most important problems in the use of BIM lies in the issues around interoperability (see Section 2.3), when part of the information of a BIM model generated in one software needs to be exchanged to be reused in another. Each stage of the design process deals with specific information according to the task to be performed (cost estimation, quality control, planning, prepare tender reports and others). The exchange of information among such applications is more complex when it spans different stages of the design process and agents are less familiar with the others' needs. This represents a challenge since BIM models are stored in structured and complex databases. Specific naming conventions are used in them to describe the contents as well as specific procedures to encapsulate the relationships and assembly rules of building components (Day, 2014).

2.2.2. Modelling based on components

As mentioned in the introduction of this chapter, the adoption of BIM by the industry constitutes a paradigm shift in which the information about buildings becomes represented by three-dimensional models built as the assembly of components (Eastman, Teicholz, Sacks, & Liston, 2011). These components are digital representations (objects) that "know" what they are and how they relate to other objects in the model. They may also include information to describe their behaviour in a particular context. Furthermore, the information contained in a BIM model should be consistent and not redundant, so that any changes in the component can be automatically updated in all affected views.

Eastman et al. (2011) pointed out that one of the central issues in understanding BIM lies in the concept of parameterization, where a "parametric object" is described as a representation consisting of "geometric definitions and associated data and rules". This means that an object that represents a "wall" in a BIM model must behave as a wall when it interacts with other objects. These relationships can be defined at nesting level and according to the component's connectivity with other components. The way in which these relationships are established depends on the design rules implemented in each BIM software tool. For example, a "wall" may include other (nested) components such as "doors" or "windows", which should know for example that a door starts at the bottom of the wall while a window can be placed at any height.

A proper definition of these components, especially in terms of their geometry, is necessary to ensure the quantity surveying process, where the amount of material is extracted for each component of the model in order to provide an estimation of the costs. Here, different situations need to be considered according to the relationships between the components. For example, if the modelling program conceives the relationship between windows and walls as "walls can contain windows", this implies that the openings in the wall can be excluded when the amount of material for walls is quantified. In another example, the relationship between walls and columns can be defined as "walls are connected to columns". These relationships vary depending on the BIM authoring tool, and present a clear example of the problems to be addressed when designers want to export a building model to another application using standardized formats (e.g., IFC standard). For the same token, reusing parametric building components throughout various BIM authoring tools becomes problematic.

2.2.3. The implementation of BIM in public procurement

The motivation behind the adoption of the BIM methodology in public projects, which typically deal with large buildings, is motivated by obtaining cost savings. As we indicated in Section 2.1, cost savings are expected to be achieved by public administrations as a result of its adoption. The main benefits are expected to derive from a more efficient management and evaluation of the project information to be delivered. Cost saving policies, however, are not exclusive to the construction sector. Usually they are aimed at all procurement systems. In 2012, the European Union announced in the report "Delivering savings for Europe: moving to full e-procurement for all public purchases by 2016" that "public entities that have already implemented e-procurement report savings of between 5% and 20% of their procurement expenditure" (European Commission, 2012).

Administrations can be involved in bidding for public works at different levels: national, regional and municipal. Therefore, in this transition towards BIM, they must adapt their delivery methods according to their administrative role. It is regularly stated that project deliveries in BIM formats can provide more guarantees about the consistency of the building designs and allow public administration workers to check the restrictions and constraints through semi-automatic processes. In addition, shortcomings and inaccuracies in the design, for example due to unresolved clash detection problems, can be more easily identified than in 2D CAD drawings. All these benefits are leading the administrations (e.g., municipal authorities, departments of regional policy and public works, among others) to start requiring BIM as a delivery format (e.g., IFC, Revit and BIMx).

With this increasing interest from public administrations, different countries have recently started to define directives, recommendations and guidelines on how public works projects should be developed to make them more efficient in terms of costs and time. In Europe, efforts in this direction are being led by countries like the United Kingdom, where the government has defined public procurement directives. These are aimed at bringing the industry toward more collaborative scenarios as a measure to reduce the costs. Similarly, other countries like Finland, the Netherlands and Denmark have also defined public procurement directives and protocols with this same objective. However, in countries like Spain it seems that some public administrations are still not decided about the data requirements in the delivery of BIM-based projects, while there are others which are still looking for ways to integrate these directives and protocols into the day-to-day practice.

In a broader context, the European Union Public Procurement Directive (EUPPD)[18] was approved in 2014 with the aim of updating the old procurement regulations by simplifying procedures and making them more flexible. Within this strategy, a recommendation on the use of electronic tools for public works contracts and design contests is included.

2.2.4. Maturity of industry

In order to be more efficient in the development of building projects for the public works sector, aligned with the cost savings policies, governments in some countries have started to elaborate different mandates defining how the industry should work through the use of the BIM methodology for a better collaboration in projects. To succeed in the elaboration and application of these mandates, it is important that governments and institutions responsible for their elaboration are aware of the maturity level of the industry in their country. This requires – in part – an analysis of whether professionals, companies and institutions are able to adapt their working methods to each level of requirements defined in such mandates and how long it would take them.

Different mandates, programmes, and road maps have recently been developed. For example, the government of the United Kingdom has been one of the first countries in Europe to define a schedule to enforce the industry of this country to move towards higher levels of maturity, which must be achieved over time, to work collaboratively in BIM-based projects as a prerequisite for bidding. These maturity levels were diagrammed in a maturity model introduced by Mark Bew and Mervyn Richards in 2008, also known as the “BIM maturity model”, in order to help industry players be more aware of the implications (Figure 2.4). This is divided into four levels (0–3), where the collaboration

[18] “The adoption of the directive, officially called the European Union Public Procurement Directive (EUPPD), means that all the 28 European Member States may encourage, specify or mandate the use of BIM for publicly funded construction and building projects in the European Union by 2016. The UK, Netherlands, Denmark, Finland and Norway already require the use of BIM for publicly funded building projects” (Autodesk, 2014).

between agents moves from uncoordinated forms using 2D/CAD programs towards the use of 3D/BIM programs, across different levels where technologies and standards are combined to facilitate the exchange of information, all this to achieve the ultimate goal of reaching a fully integrated project delivery (IPD).

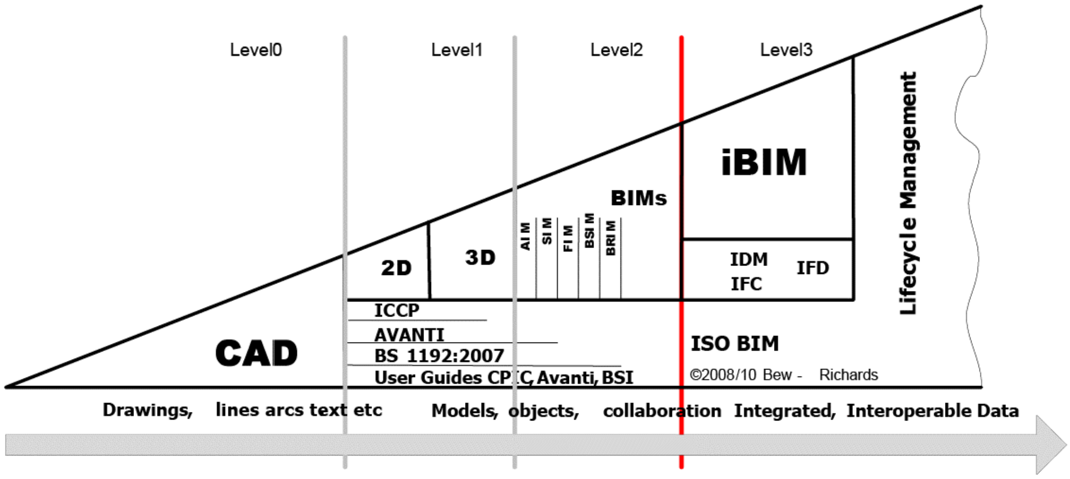

Figure 2.4: BIM maturity model (Bew & Richards, 2008).

The concept of maturity levels in the UK is somewhat different to the concept of three BIM capability stages defined by Succar in 2009 which were later expanded to five. According to Succar (2010), there are three consecutive stages of capability that an organization or project team passes through as they adopt BIM tools and workflows: (1) Object-based Modelling, (2) Model-based Collaboration, and (3) Network-based Integration. In Object-based Modelling, each industry player generates an information model for their own use; in Model-based Collaboration, each pair of industry players exchanges data directly between them through proprietary and non-proprietary file formats; and in Network-based Integration, industry players work collaboratively on a centralized (federated or integrated) information-rich model (Figure 2.5).

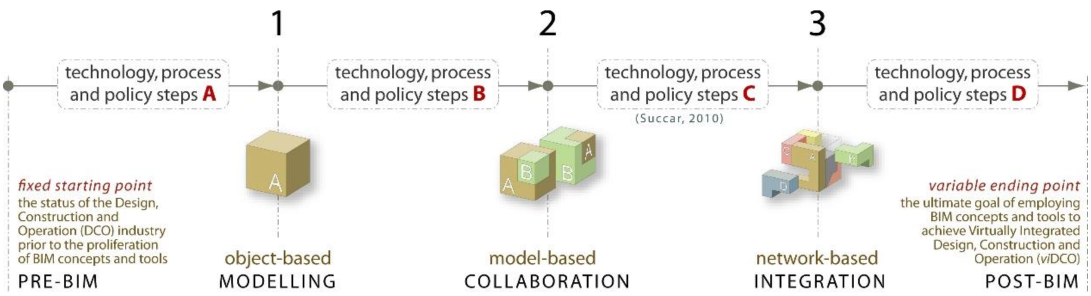

Figure 2.5: Linear view of the BIM capability stages (Succar, 2010).

In addition to BIM capability stages, Succar (2010) identifies five BIM maturity levels, with "BIM maturity" defined as "the quality, repeatability and degree of excellence within a BIM capability", where "BIM capability" means "basic ability to perform a task or deliver a BIM service/product". The five maturity levels – (a) Initial/Ad hoc, (b) Defined, (c) Managed, (d) Integrated and (e) Optimized – are represented in the BIM Maturity Index (BIMMI), which is used to assess multiple technologies, processes and areas (Figure 2.6).

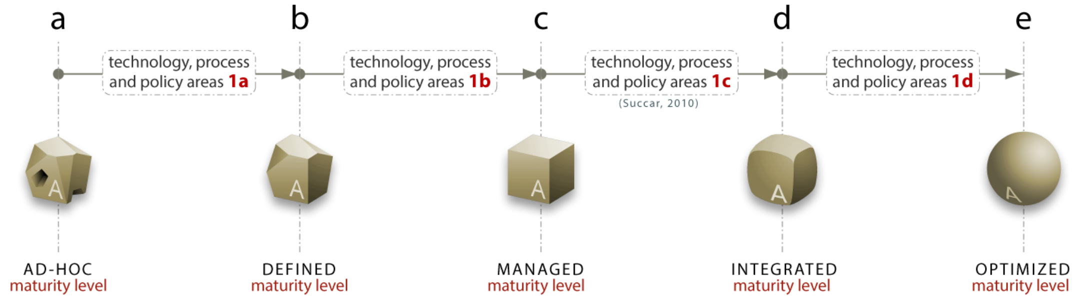

Figure 2.6: Linear view of the BIM maturity levels (Succar, 2010).

Another example of a tool implemented to assess the maturity level of BIM in projects is the “Arup BIM Maturity Measure”, created at Penn State University in 2014. This is a discipline-agnostic tool that analyses the successes and areas for improvement in the use of BIM.

2.3. Interoperability

In previous sections we stated that BIM-based projects, and building projects in general, must face the problem of data exchange. Different aspects make this exchange complex, particularly when considering the various disciplines that intervene, involving multiple actors, each one with a particular vision and understanding of the project.

In the context of information technologies, the capacity to make information generated in an information system understandable for another is known as “interoperability”. This concept involves: (1) an exchange of information without losses and (2) a correct interpretation of information, where the first condition is a prerequisite for achieving the second. By considering them in the data exchange between software tools and systems used in the AEC industry, it can be stated that full interoperability is presented as a difficult challenge to be achieved.

Usually the design of medium and large buildings involves using different BIM software applications to carry out specific parts of the design (architectural, structural, MEP, etc.). These applications have implemented their own methods and rules to adjust the modelling capacities according to different aspects (disciplines, design methods, etc.). This heterogeneity makes the exchange of information between different applications complex.

2.3.1. Concept and types

The IEEE Glossary defines interoperability as “the ability of two or more systems or components to exchange information and to use the information that has been exchanged” (Geraci, Katki, McMonegal, Meyer, & Porteous, 1991). This definition refers to transferring information from one system to another without significant losses. Another definition is provided by the European Interoperability Framework (EIF)[19], which defines interoperability as "the ability of disparate and diverse organizations to interact towards mutually beneficial and agreed common goals, involving the sharing of information and knowledge between the organizations via the business processes they support, by means of the exchange of data between their respective information and communication technology (ICT) systems" (IDABC. Enterprise & Industry DG, 2004). This second definition refers to the need to interpret information. Therefore, an exchange of information without losses is a prerequisite for interoperability, but it is not a sufficient condition.

Interoperability can be classified in different manners. For example, the EIF (2010) and European Telecommunication Standards Institute (ETSI)[20] indicate that most interoperability frameworks adopt a three-layer structure, distinguishing between technical, semantic and organizational interoperability. However, other ways to classify interoperability can be found in the literature review. Some of them refer to the ability of information systems to work together. Other approaches focus on considering aspects such as the ability of systems to interpret information, distinguishing between three types of interoperability: physical, syntactic and semantic.

According to Obitko (2007), "physical interoperability" refers to the basic technological infrastructure supported by a variety of protocols and standards for communication between information systems; "syntactic interoperability" refers to the ability of the programs to correctly analyse a data model, for example described in a file, without errors in its interpretation; and "semantic interoperability" concerns the ability of information systems to reach a common understanding of the meaning of the information that must be exchanged. Semantic interoperability is defined by European Interoperability Framework as "the ability of information and communication technology (ICT) systems and the business processes they support to exchange data and to enable the sharing of information and knowledge: Semantic Interoperability enables systems to combine received information with other information resources and to process it in a meaningful manner" (EIF, 2012).

The transmission of meaning (terms and expressions) in semantic interoperability requires common agreement on the meaning of terms to be reached. This assumption inspired the creation of organisms for standardization, such as the ISO Technical Committees aimed at providing a common meaning of terms within a domain (Veltman, 2001). In the AEC industry, the interoperability between software applications is facilitated through different standards. The most commonly used are the IFC (ISO

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[19] The European Interoperability Framework (EIF) is aimed at promoting and supporting the delivery of European public services by fostering cross-border and cross-sectoral interoperability; guiding public administrations in their work to provide European public services to businesses and citizens; and to complement and tie together different National Interoperability Frameworks (NIFs) at European level. EUROPEAN COMMISSION. Bruxelles, le 16.12.2010. COM (2010) 744 final.

[20] The European Telecommunications Standards Institute (ETSI) is a non-profit organization that produces ICT standards for the telecommunications industry.

16739:2013, 2013) and those covered by the "Building construction – Organization of information about construction works" (ISO 12006).

Semantic interoperability in BIM-based projects aims at providing a common understanding of the information to be shared, which is mainly represented by digital models of the building to be exchanged between different actors. Standardised semantic representations of these models facilitate their processing in different ways (to perform analyses, checks, etc.) and, consequently, increase the efficiency and quality of the design process (Steel, Drogemuller, & Toth, 2012). For example, analysis and checking on these models can become more efficient when they can be automated.

2.3.2. Review and current state

Since the appearance of the first computer programs and tools for the construction field, one of the main problems for interoperability is the use of proprietary formats as the primary mechanism to extract the information. This problem was pointed out by Bo-Christer Björk (1995), who also indicated that another problem for interoperability is in the fragmented organizational pattern within the building industry. In the 1980s there was the belief that the data exchange could be improved to the extent that software developers were aware of the need for the industry to work collaboratively, and in this way provide more powerful mechanisms to export the information to the programs that must make use of it. This idea was illustrated in the archipelago of Hannus, Penttilä and Silén in 1987 (Figure 2.7).

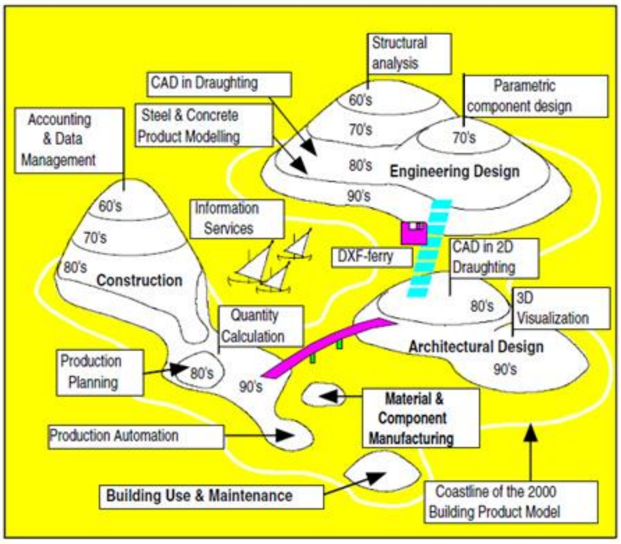

Figure 2.7: "Islands of automation within the building process" (Hannus, Penttilä, & Silen, 1987).

However, despite all the progress made since then, the underlying problem persists and has even become more complex with the advent of BIM. Currently, progress in developing more powerful BIM applications capable of handling large parametric models of buildings has resulted in a greater degree of BIM model specification. This increase in the specification leads consequently to a difficulty for the exchange of information and make it interpretable for other BIM applications.

The difficulties to exchange data posed by the ever-increasing BIM models suggests that a global change should take place across various realms, starting by reaching a consensus among BIM software developers to define the basis for a fully compatible BIM model. Obviously, this scenario is unlikely for several reasons. Leaving aside the commercial interests of the software vendors, this agreement would imply the implementation of the same, or at least compatible, modelling rules in all software applications. This possibility does not make sense given that each task in the modelling is subject to a set of conditions that are rooted in the design methods provided in these applications (e.g., human-computer interaction provided by the tool, the discipline, parametric rules and capabilities implemented, and others).

However, the homogenization of BIM models seems to be moving in the opposite direction to the one adopted by software vendors. They improve their software packages after their particular understanding of how building designers should work with them. Although new versions of BIM applications include additional capabilities, functionalities and approaches to facilitate the modelling, they still do not pay much attention to making the software more interoperable.

Despite all the advantages achieved in the BIM applications, the most common data exchange method used today in the AEC industry is still through exchanging files. The way in which these files are exchanged has become more practical in recent years with the advent of cloud-based collaboration tools and Internet platforms (e.g., Flux.io[21]). However, none of these cloud solutions solve the underlying problems of interoperability between software of different vendors.

2.3.3. Software applications

During the last decades, software used in the AEC industry has evolved from 2D Computer-Aided Design (CAD) applications and paper towards semantically rich 3D digital models (Steel et al., 2012). However, the fragmentation of this industry is leading to different degrees of maturity in the use of BIM among the different actors. A significant part of the industry still seems to lack knowledge about its benefits. For example, many agents are still using conventional 2D/CAD systems while others are using BIM authoring tools but in isolation, so they are not really applying the BIM methodology.

Although the variety of software applications currently used in BIM-based projects is wide, they can be classified into two main groups: design and calculation (including simulation and analysis). The implications for data exchange in both types of applications is different since they have different purposes and types of information to handle. Design applications that refer mainly to BIM authoring tools are intended to allow designers to model 3D parts of a building according to each discipline (architectural, structural, MEP, etc.). These applications have implemented their own geometric and parametric rules, which are supported by the particular data structures created for each case. This heterogeneity results hinders the translation of contents from one system to another. The

[21] Flux.io. Retrieved from https://flux.io/.

difficulties involved in translation depend on the information that need to be exchanged in each case. For example, the exchange is usually less complex between design applications and calculation tools than between design applications. In the first case, the information to be exchanged is more specific, simple and controlled.

Other applications used in the process of building design, but not used exclusively for this stage, are those aimed at providing a 3D visualization of the designs. These applications do not usually involve interoperability problems, since their only function is to visualize the information described in the model, usually provided through a file. Visualization applications, more commonly called “viewers”, are usually compatible with the IFC standards (IFCViewer[22], Tekla BIMsight[23], and others). Related to the visualization applications are those based on checking and coordinating models (e.g., Solibri Model Viewer[24]). Both can be used to coordinate and control the partial and final results of design development.

Problems involved in the representation of building models, particularly when these are provided in the IFC standard, arise when the model representation does not match the expected result. This situation usually leads to the dilemma of whether the problem is a consequence of the export process, or otherwise, to a misinterpretation of the information by visualization applications. To isolate the problem, users typically end up importing the model in various visualization applications. Then, they check the results and extract their own conclusions.

Other visualization applications are intended to produce renderings and 3D animations to provide previews of the building to be constructed. The target audience of these previews is usually owners and promoters of the project in order to verify the results and take decisions, if necessary.

Currently, more and more architectural and engineering firms are adopting BIM methodology to create their building designs. These firms typically use BIM authoring tools that have been designed from a global usage perspective, for example those produced by companies such as Autodesk, Nemetschek, Graphisoft, Tekla and Bentley. The current limitation in the capabilities provided by these tools lies in their all-embracing approach. Consequently, the integration of functionalities aimed at providing specialized calculations of building designs, for example according to the regulations of each country and region, is presented as a complicated issue. It seems easier for local software developers, and those that are specialized in a particular discipline, to have a good understanding of building regulations and how they should be calculated. In most cases, these developers are national companies with a long history and experience in their field over the years. This makes it easier for them to develop applications (e.g., Cypecad[25],

[22] IFCViewer (RDF). Retrieved from http://rdf.bg/ifc-viewer.php.
[23] Tekla BIMsight (Tekla). Retrieved from http://www.teklabimsight.com/.
[24] Solibri Model Viewer (Solibri). Retrieved from https://www.solibri.com/products/solibri-model-viewer/.
[25] Cypecad (Cype). Retrieved from http://cypecad.cype.es/.

Tricalc[26], Civilcad[27]) tailored to national regulations (e.g., at the Spanish national level: CTE[28], EHE[29], RITE[30] and REBT[31]). This reality leads to industry players to have to exchange information between BIM design and specialized calculation applications.

In order to anticipate interoperability problems between software applications in BIM-based projects, different data exchange scenarios should be analysed before starting to work. Knowledge about the export and import capacities of the applications involved in each possible scenario helps to achieve the required level of interoperability.

2.3.4. Planning data exchange

Interoperability problems in building projects can be anticipated by planning the data exchange considering the different aspects involved (users, programs, type of information, level of detail, etc.). Specific requirements are generally included in documents after an agreement has been reached among project stakeholders. These interoperability requirements need to be defined in great detail in BIM-based projects because the data exchange involves more complex and diverse information (e.g., 3D models, planning data, and material properties).

Documents outlining the data exchanges are becoming powerful and useful tools for managing project information, first, as a statement of intent, and second, as live documents to be used during the project development to provide more details about the data exchange. Project planning is more useful and effective in IPD projects, where all prime actors (owner, designer and constructor) can participate from the early stages. This way, IPD enables a greater anticipation of possible problems, both in the design and construction phases, since the requirements can be specified with the participation of all the partners involved.

Different standards and guidelines have emerged in the last few years in response to the need to specify how the information should be exchanged in the different stages of a building project. An example is the Singapore BIM Guide (Seng, 2012), which describes the roles and responsibilities of the industrial agents who are involved at different stages of BIM projects. Another example is the PAS 1192-2 specification, which is included in

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[26] Tricalc (Arktec). Retrieved from http://www.arktec.com/EN/Products/Tricalc/Features/Features.aspx.
[27] Civilcad (Arqcom). Retrieved from http://civilcad.com.mx/.
[28] The CTE (Código Técnico de la Edificación) is the regulatory framework that establishes the requirements to be met by buildings in relation to the basic requirements of established security and habitability in Spain.
[29] The EHE (Instrucción Española de Hormigón Estructural) provides the regulatory framework laying down requirements to be met by concrete structures to meet the requirements of structural safety and security in Spain.
[30] The RITE (Reglamento de Instalaciones Térmicas en los Edificios) establishes the conditions to be met by facilities designed to meet the demand of thermal welfare and hygiene through heating, cooling and hot water for rational use of energy in Spain.
[31] The REBT (Reglamento Electrotécnico para Baja Tensión) establishes the technical conditions and guarantees to be met by electrical installations connected to a power supply with low voltage limits in Spain.

the Publicly Available Specification (PAS) and defined following the guidelines set out by the BSI (British Standards Institution). This specification is intended to support the requirements for achieving Level 2 of BIM maturity according to the strategic plan for an efficient AEC industry in the United Kingdom. This specification provides guidance for defining the appropriate level of detail of the information in each stage of BIM projects.

In order to be efficient in the BIM project delivery process it is necessary to develop a detailed execution plan for BIM implementation (CIC, 2010), also known as the BIM Execution Plan (BPEP) or BIM Project Execution Plan (BPEP). A BEP includes the specification of data requirements. One of the first guidelines for its specification is the "BIM Project Execution Planning Guide", created at Pennsylvania State University from the conclusions of the thesis developed by Chitwan Saluja (2009). The guide states that good BEP documentation "will ensure that all parties are clearly aware of the opportunities and responsibilities associated with the incorporation of BIM in the project workflow" (Saluja, 2009). Countries like the United Kingdom, Australia, New Zealand, Singapore and others have developed guidelines based on the BEP tailored to their own needs.

2.3.5. Data requirements

In recent years, more flexible methods for capturing data requirements in building projects have been conducted by the research community. An example is the ReqCap tool, officially called BIM*Q[32], which is based on the IDM/MVD (Section 2.4.3) approach (Figure 2.8). This tool was implemented by the buildingSMART Norwegian Chapter[33] in collaboration with the AEC 3 Company. The use of this tool, which has been mandatory in Norway for public procurement projects since 2015, allows users to capture data requirements – employer's information requirements – for different stages of the building life cycle. These requirements are meant to answer questions like "*who delivers what, when, and how?*" (Weise, Liebich, Nisbet, & Benghi, 2016). Some research projects[34] have contributed to improve this tool. For example, the tool was used and improved during the development of the SWIMing project[35] (2015–2017). The aim of this project is to standardize the data requirements defined in European research projects developed in the area of energy efficiency in buildings. In this case, the BIM*Q tool is used to provide support in structuring data requirements in order to identify similar use cases. This way, it is possible to find common data structures among them. These use cases are related to a larger list currently developed by the W3C Linked Building Data Community Group (LBD)[36]. The objective of this tool is the creation of a database of data

[32] BIM*Q, AEC 3. Retrieved from http://www.aec3.com/de/kompetenzen/BIM-Q-Database.htm.
[33] BuildingSMART Norway Chapter. Retrieved from http://buildingsmart.no/.
[34] Streamer. Retrieved from http://www.streamer-project.eu/,
Eneff-BIM. Retrieved from https://www.ise.fraunhofer.de/de/forschungsprojekte/eneff-bim/,
R4SC. Retrieved from http://www.ready4smartcities.eu/.
[35] SWIMing. Retrieved from http://www.swiming-project.eu/.
[36] W3C LBD Community Group. Retrieved from https://www.w3.org/community/lbd/.

requirements for the different use cases across the whole building life cycle in order to support data exchange across those use cases.

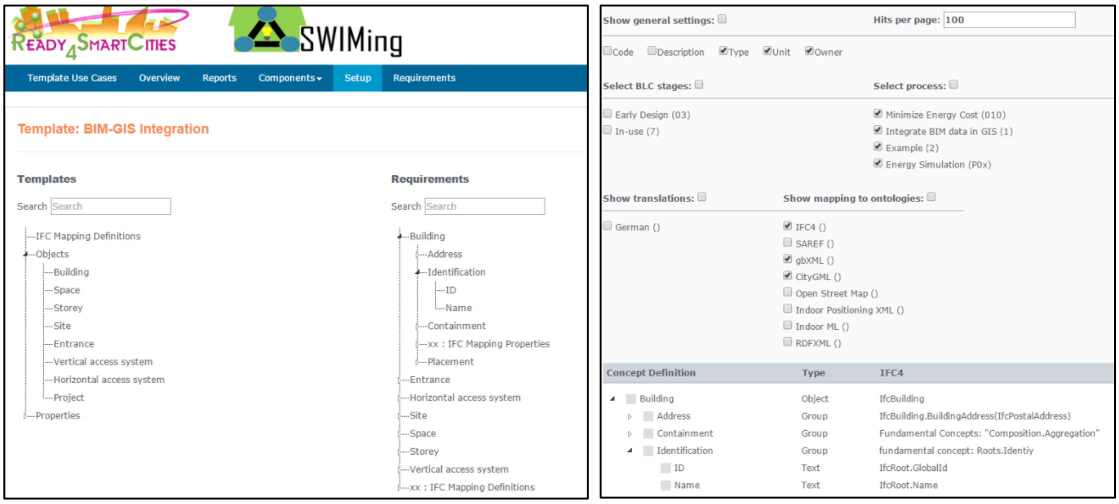

*Figure 2.8: Screen-shots of the BIM*Q tool interfaces showing the data structure that suits the requirements generated from a template.*

However, because the design and construction of a building is a living process, not all data requirements can be defined in advance. This means that there are certain types of decisions made near to its completion that are difficult to anticipate. A typical example is the choice of products, which can lead to reconsidering other parts of the design.

2.3.6. Levels of development

An increasingly important data requirement when exchanging information between different agents in BIM-based projects is the level of detail (LOD) of the information required by the recipient.

As a general concept applied in building design using software tools, the level of detail mainly refers to the precision and quality in which elements are represented (e.g., according to the number of polygons used for their 3D representation). The use of this concept in CAD systems dates back to the 1970s. One of the pioneers in providing algorithms to manage different levels of detail in 3D geometric models was James H. Clark in 1976. The level of detail may vary depending on the requirements to represent the information of the model in different situations. For example, the level of detail necessary to provide photorealistic 3D renders will be higher than the required to carry out the modelling of the design (Madrazo, 1989, 1990).

Nevertheless, the concept of level of detail applied in the BIM domain has acquired a more specific meaning according to the needs and uses of BIM models. Currently, there is more than one meaning associated with this concept. One of them concerns the information of the components that is required in a specific stage of the project, including not only geometry. This meaning introduces a substantial change with respect to the previous definition, focusing on what information is required rather than referring to the amount of information included in general. This way, the levels defined in the level of detail do not necessarily increase with the level of detail in the geometric elements, but rather depend on the information (graphical and non-graphical) that is required during its development. For example, contractors may be interested in knowing the reference code of the manufacturers' products, or the codes that will eventually be used in the construction of the building. Adding this information into the model to be exchanged may involve a higher level of detail, while the geometric information remains the same.

The use of the term in relation to the needs and uses of BIM models was introduced by Vico Software[37], in 2004, for the specific case of the information of the components that is necessary to carry out the cost estimation. Later, the concept was adopted by the AIA (American Institute of Architects) after observing its potential to assess the quality of BIM models according to different uses. To disambiguate the meaning of the term "detail" – which can be interpreted as graphical detail – from the information that can be required for a specific process, stage, delivery, uses of BIM, etc., the name was changed to levels of development (Weygant, 2011). The specification of these levels was first provided in the document *AIA E202–2008: Exhibit Building Information Modeling Protocol* (AIA, 2008), a guide to help organize the requirements for the development of design through BIM modelling. The definition was later expanded in the document *AIA G202-2013, Project Building Information Modeling Protocol Form* (AIA, 2013). To help identify the level of development, from now on LOD, components of a model can include a parameter indicating the LOD level through a number defined according to a standard.

As described in the document *Level of development specification* published by BIMForum (Bedrick, 2013), the information about building components in a BIM can be classified according to six levels (100, 200, 300, 350, 400 and 500). This way, for example, LOD 100 means that building components in a model are defined only as conceptual models and may be graphically represented by a symbol or other generic representation, while LOD 200 should include more accurate graphical information about the components that are represented as generic objects or systems with approximate size, shape, location and orientation, and non-graphic information. LOD 300 provides more accuracy in terms of size, shape, location and orientation available for a basic geometry coordination compared to the previous level. The need for greater precision in defining the geometry for clash detection checking processes, and full coordination in general, resulted in LOD 350. LOD 400 adds detailed information about detailing, fabrication, assembly and installation to the 350 level, while LOD 500 defines the information about the element in terms of "as-built" and as a verified field representation. An LOD numbering can be applied at different scales, for example over the whole building model, and its components, and also to define their relations and how they are connected to each other (Figure 2.9).

[37] Vico Software (part of the Trimble group). Retrieved from http://www.vicosoftware.com/.

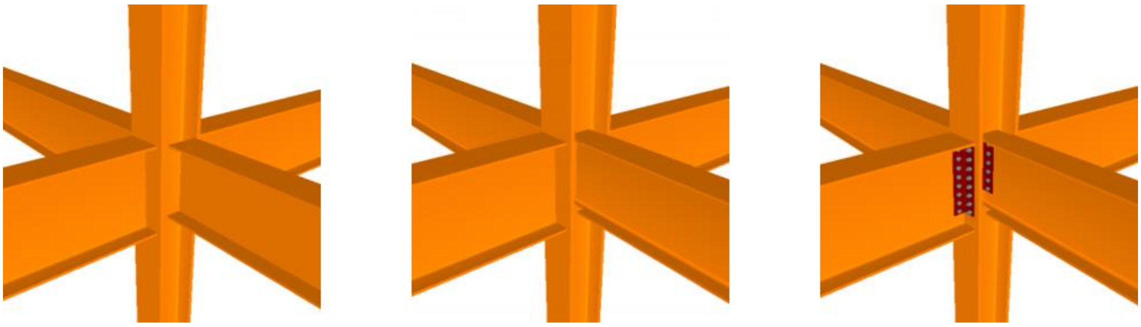

Figure 2.9: Example of connected structural elements represented by three different LOD: 300, 350 and 400 (BIMForum, 2015).

LOD levels defined according to this system are associated with a specific range of stages in which they can be applied (Figure 2.10). The specification of levels provides a general reference for project planning. However, the numbering structure, with levels specified per hundred, enables adding extra numbers. This way, intermediate LOD levels can be added to define more specific requirements depending on the needs of projects stakeholders (e.g., LOD 295 to check fire safety).

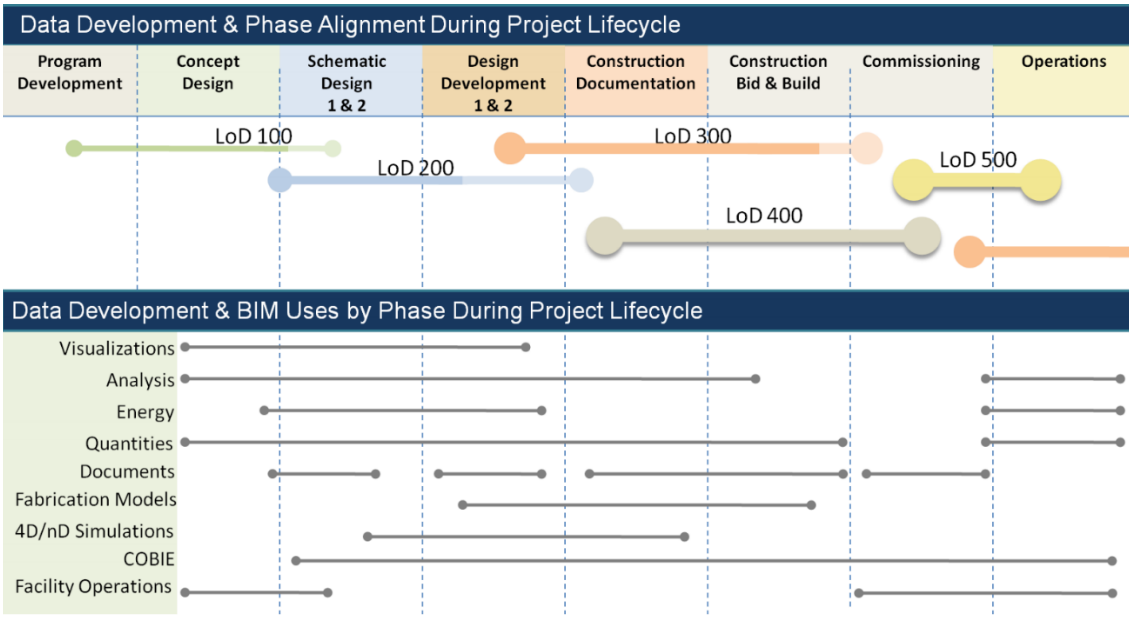

Figure 2.10: Relation between project stages and LODs (Davis, 2010).

Another convention to specify the LOD in BIM was provided by the AEC (UK) Initiative[38]. This specification is aligned with industry protocols, specifications and documents intended for implementation and use of BIM technologies in that country. It comprises six levels: (1) Symbolic, (2) Conceptual, (3) Generic, (4) Specific, (5) Construction, and (6) As-built. In contrast to the LOD approach proposed by the AIA, these levels are not intended to be used in a specific stage.

[38] The AEC (UK) Initiative is a group formed in 2000 by different companies from the AEC industry in the United Kingdom.

Other classification systems of the detail level of the components of a BIM model are based exclusively on geometric information. For example, the AEC (UK) BIM Protocols have defined specific levels for the graphic representation of the elements. These levels correspond to the symbolic (G1), placeholder (G2), suitable for construction (G3) and fully detailed objects with high resolution (G4) ("AEC (UK) BIM Technology Protocol", 2015). As opposed to these classification systems, other systems focus on non-graphical information of BIM models which is related to the term "level of information" (LOI).

The LOD specification provides some advantages to help the project planning. However, its management during the development also has to overcome some difficulties and challenges. One of them is that the information that should be available in a BIM model in relation to each LOD level is imprecise and is not entirely clear (Berlo & Bomhof, 2014). Another difficulty arises when a design is developed using models of components that have already been created, for example, those available in online catalogues or in the internal library of programs. The information provided in these models is usually specified in a single way, which may vary depending on the type of component. Therefore, when architects and designers include these models to create building designs, they are likely to have to deal with components with different LOD levels coexisting in the same BIM model. It is expected that in the future, models of products will be able to be retrieved from the catalogues according to a specific LOD level.

2.3.7. Building classification systems

A classification system can be defined as an organized structure to structure information in categories. The application of this concept in the BIM domain can be useful to classify the components of a model according to their usage, function type, and so on. This classification provides an additional level of organization of the BIM model.

In building projects, the organization of components according to a classification system can be useful for supporting the modelling activity. This support includes the internal management of the model, but also the coordination of the design across the different disciplines involved in a project. For example, classification systems are a mechanism to support data exchange between project participants (Jørgensen, 2009). This way, classification systems can be created, or adapted from existing ones, by each agent for internal use, and/or used as a shared reference for those who participate in a project.

Among their benefits, classifications can facilitate the search, location and selection of one or more components in the model. This is particularly useful in large models. Currently, the mechanisms provided in the BIM authoring tools do not provide the necessary support to facilitate these operations. For example, these tools do not allow users to filter components of a BIM model based on keywords included in the name of the parameters (e.g., defined through a concatenated numbering nomenclature).

Different specifications of standardized classification systems have emerged over the last few decades in an effort to organize the semantic structures in this industry. Most of them have been intended to provide common criteria for organizing the information in BIM models, mainly the components, according to different criteria (functions, activities, spaces, systems, etc.). These standardized classifications started at the local level, according to the reality surrounding the building design and construction methods of each country. However, their popularization and adoption by other countries has led the industry to call them “international classification systems”.

The most popular international classification systems currently used by the industry are Uniclass[39], OmniClass[40], Uniformat[41] and MasterFormat[42]. Although these standards differ in the level of granularity in their definition and how they are organized, they are intended to harmonize the concepts based on the same meaning. Some difficulties need to be considered when using these systems:

1. Adjusting to the different criteria and requirements in the internal organization of a project.
2. Providing a common structure taking into account the multidisciplinary nature of the agents in a project.
3. Providing the appropriate level of granularity.

In the first case, the difficulty lies in the variability of needs of each project, making them difficult to standardize. In the second case, the problem lies in the need to classify information in the most appropriate way according to each discipline. For example, the organizational structure and working practices of builders and subcontractors differ widely (Knopp-Trendafilova, Suomi, & Tauriainen, 2009). This leads to requiring simple and not low-level hierarchies. Finally, in the third case, the difficulty in providing the appropriate level of granularity lies in the variability of each discipline and the scope (international, country, region or municipality). For example, the more generic these rules are, the more difficult it will be to meet the specific needs of each discipline. Other difficulties in the use of international classification systems lie in the reluctance of some companies to use them, especially when they already have their own classification systems optimized for their processes (Dikbas & Ercoskun, 2006).

[39] *UNICLASS*. The Unified Classification for the Construction Industry is a classification system published in 1997 by the Construction Project Information Committee (CPIC) for organizing information available for all participants throughout the life cycle of a project; this includes organizing library materials and for structuring product literature.

[40] *OMNICLASS*. The OmniClass Construction Classification System (or OCCS) aims to unify MasterFormat, Uniformat, Uniclass and other classification systems derived from standards developed by the International Organization for Standardization (ISO) and the International Construction Information Society (ICIS) subcommittees and workgroups into a single system based on ISO 12006-2. OmniClass is considered one of the main candidates to receive future acceptance from the AEC industry, not only for project management, but also as a classification system intended to be used to search and compare products.

[41] *UNIFORMAT*. Is a method to organize information about a building into a standard order on the basis of building elements (often referred to as systems or assemblies) or parts of a building characterized by the function, without regard to the materials and methods used for the construction.

[42] *MASTERFORMAT*. Standard used to organize specifications and create contract documents for building design and construction – specially used in countries like the US and Canada. This standard was published by the Construction Specifications Institute (CSI) and Construction Specifications Canada (CSC) in order to provide a classification to organize data about construction requirements and activities, but mostly focused on products. Its main use is to facilitate the communication between designers, contractors and builders to meet the requirements and cost estimations of a project (Mowrer, 1994). Currently, MasterFormat is included as “Table 22 – Work Results” in the OmniClass standard classification.

This panorama suggests that solutions for managing, combining and mapping internal and local classifications (generated in the context of a project domain) with standard classification systems are required, as well as between standardized classification systems (e.g., between national and international systems). This way, in federated BIM evelopments, agents involved in a building project can develop their part of the model according to the classification system that best meets their need. Later, they can exchange their part of the model with another agent and the classification can be readjusted according to the needs of this new agent.

Today, some tools, plug-ins and functionalities included in BIM authoring tools enable the organization and management of classifications across BIM models. These solutions facilitate the inclusion of various parameters related to different classification systems (both internal and standard systems), for example the Autodesk Classification Manager[43] plug-in for Revit. However, tools to facilitate an automatic mapping between different standardized classifications systems, or between these and those created by end-users for internal use, are still missing.

Classification systems can also be useful, for example, to help users to relate components and products of a BIM model with the regulations to which they are subjected. Some research works have been conducted in the last decade with the aim to facilitate mappings between taxonomies based on classification systems and regulations. For example, Cheng, Lau, and Law (2007) proposed a systematic approach to mapping regulations to industry-specific taxonomies to increase the usability in their application. Through the links established among taxonomies, practitioners may be able to browse through regulations to find out how to comply with the requirements of a project. Three methodologies have been used to cluster concepts from different taxonomies to map them to regulations (1-1, 1-n and n-1). The methodology was applied in a case in which concepts from the OmniClass and IFC standards are mapped to concepts of the International Building Code (IBC)[44].

2.4. Standards and technologies

The use of standards in industries in general contributes to improve the quality, reliability and efficiency in the production of products and services so that they become more competitive. Most of them are international standards promoted and supported by the International Organization for Standardization (ISO)[45]. When analysing the use of standards to facilitate the interoperability in data exchange, it is clear that each industry has its own constraints. As discussed at the beginning of the previous section,

[43] Autodesk Classification Manager plug-in for Revit, CADD Microsystems. Retrieved from http://www.biminteroperabilitytools.com/classificationmanager/

[44] The International Building Code (IBC) is a specification developed by the International Code Council (ICC), whose first version was launched in 2000, designed to be compatible with the International Codes published by the ICC.

[45] International Organization for Standardization (ISO). Retrieved from http://www.iso.org/.

interoperability is necessary in the development of building projects to provide the right information in the right format at the right time (Eastman et al., 2011). Reaching a desirable interoperability is essential to avoid the recreation of parts of the design model, or in the worst case, the recreation of the entire design from scratch. To achieve this aim, the most appropriate solution for data exchange must be considered in each case.

Since the advent of CAD tools, the most used mechanism for data exchange has been through *file formats*. These can be classified mainly into two groups: proprietary and open formats. One of the first formats designed to facilitate interoperability in data exchange was DXF (Data eXchange Format)[46]. Designed by Autodesk, the format was introduced in 1982 with the first version of the AutoCAD program to provide interoperability between this software and others. However, the lack of support to adapt it to the new challenges that arise in the development of BIM-based projects is currently limiting its use. Since the use of open standardized formats remains crucial to facilitate interoperability in data exchange between BIM applications and to overcome the constraints imposed by proprietary formats, other standards for interoperability have taken up these challenges.

Standards for interoperability are built on common vocabularies. However, to get these vocabularies it is necessary to reach a consensus on their formal semantics and syntactic structure. Through sharing a common semantic structure among different information systems, in this case those implemented in the BIM applications, shared concepts can be used as bridges between them (Demir, Garrett, Akinci, Akin, & Palmer, 2010). The use of open formats allows users to exchange information independently of the software that has been used to generate it. However, procedures to import and export information must be implemented for each standard in each software. Conversely, the use of proprietary formats is mostly restricted to software products from the same vendor.

The specification of open standards for interoperability must deal with various limitations. For example, it seems unlikely that they will be able to integrate culture, regulation codes and other aspects that are particular to each country or region into a single schema. In addition, their elaboration requires a thorough knowledge of how the AEC software applications work, and how the data are described in them (Björk, 1992).

Most of the efforts in providing interoperability between applications through open standards are being led by the buildingSMART consortium, formerly the IAI (International Alliance for Interoperability)[47]. The aim of this consortium is to facilitate an efficient information flow during the different stages of the building lifecycle. Four core standards and technologies have been developed by the consortium: (1) Industry

[46] DXF Reference. Retrieved from http://images.autodesk.com/adsk/files/autocad_2012_pdf_dxf-reference_enu.pdf.

[47] BuildingSMART, or the International Alliance for Interoperability (IAI), is an international network of organizations, industry practitioners, software vendors, and researchers (over 600 companies around the world) working to support interoperability throughout the AEC community that aims to improve the exchange of information. Retrieved from http://buildingsmart.org/.

Foundation Classes (IFC), a data exchange format, (2) BuildingSMART Data Dictionary (bSDD), a reference library used to define the domain of information to be shared, (3) Model View Definitions (MVD) used to specify the exchange requirements defined according to a particular domain, use or application, and (4) Information Delivery Manuals (IDM) used to specify the information contained in a model according to the contracted exchange. The central issues related to the use of these standards, and technologies that support them, are analysed and documented in this section.

2.4.1. Overview of IFC

IFC is the most extended open ISO standardized data schema intended to support data exchange in the AEC industry. The first version was released in 1996 as the first standard for exchanging Building Information Models (Steel et al., 2012). Since then, buildingSMART has been actively working in the development of new versions in order to increase the level of interoperability. Each new release resolves some of the deficiencies found by the professionals in the previous version. Furthermore, some obsolete parts are removed or updated and extensions are added.

The use of open standards such as IFC is increasingly recognized as an advantage for building owners, public administrations and building government agencies and ministries[48] in some countries, it is acknowledged as a delivery format for bidding projects. Among the reasons for this decision are the following:

- It guarantees independence in the use of software applications.
- It assures that the data exchange format can be applied throughout the whole building life cycle.
- It enables any information about BIM models to be reused in the future.
- It certifies that the same rules are applied in the bidding process.
- It can be read, so it is legally binding.

From a more technical point of view, the IFC schema is based on a set of concepts, such as classes, attributes, relationships, property sets, and quantity definitions, used to describe information about building models to be exchanged between different software applications. The specification includes constructs to define a wide range of features for modelling buildings and their elements. This includes geometric representation of basic architectural elements such as slabs, columns, beams, windows, doors, etc., as well as definitions of the facilities and structural analysis.

Typically, the IFC schema is represented through the EXPRESS data modelling language (ISO 10303-11:2004, 2004), although the use of other languages (XSD, OWL) is possible as well. The information defined according to the IFC standard is exchanged between

[48] A list of countries that are supporting the use of open standards (including IFC) in public procurement projects can be found at the following link: http://iug.buildingsmart.org/resources/statements-and-guidelines/.

construction applications through the STEP Physical File (SPF) format, although the use of other languages (XML, RDF) is possible as well. SPF is a neutral file format capable of representing information about 3D objects in a human-readable ASCII structure. STEP originates from product modelling and manufacturing industries and is also used in these industries (e.g., automotive, aerospace and shipbuilding). However, the main reason for its use is that the information is encoded according to a given EXPRESS schema. This way, information about BIM models can be encoded according to the corresponding version of the IFC schema defined in EXPRESS (e.g., IFC2x3, IFC2x3 and IFC4).

The architecture of the IFC schema is divided into four distinct layers (Figure 2.11):

1. **Resource Layer.** Contains the fundamental concepts expressed as entity types such as geometry, topology, geometric model, etc.
2. **Core Layer.** Includes abstract concepts like object, group, process, property definition, relationship or root. Therefore, the concepts described in this layer enable the common rules to be defined for modelling in IFC, which are shared between all the partial models.
3. **Interoperability Layer.** Defines basic concepts for interoperability between different domain extensions. Standard building elements such as wall, beam, slab, door, roof, window, etc. are defined.
4. **Domain Layer.** Entity types and properties of this layer extend the concepts of the interoperability layer to provide schemas for processes in specific domains of industry (Structural Analysis, HVAC, Electrical, Architecture, Construction Management and others).

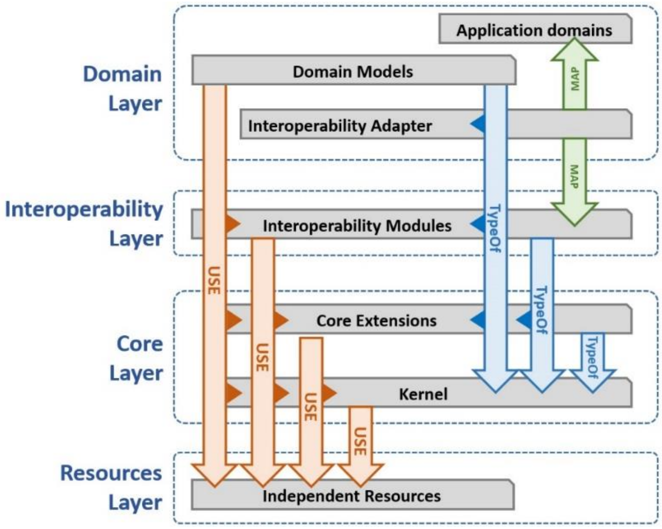

Figure 2.11: IFC data model architecture showing the relation between the four layers (Liebich, 1999).

IFC enables the information about a BIM model to be represented according to these four layers. However, the responsibility of ensuring that the information is properly defined in the model to be exchanged lies in the software application from which this model will be exported in this format. Although the exportation will be different depending on the application, most technical aspects are common. For example, one of them lies in the establishment of the relations between the entities of the IFC schema and the entities defined in the internal structure of these tools. Usually, these mappings (i.e., equivalences between entities) can be configured by users of these tools through a table provided in the settings. Figure 2.12 shows an example of the mapping table provided in Revit. In most cases, these equivalences are defined by default. Therefore, the users of these tools must redefine some mappings according to their needs, for example according to the preferences of the recipient of the model to be exported.

Revit Category	IFC Class Name	IFC Type
Structural Area Reinforcemen	IfcReinforcingBar	
Boundary	*{ IfcReinforcingBar }*	
Structural Beam Systems	IfcAssembly	
Structural Column Tags	Not Exported	
Structural Columns	IfcColumn	
Caras ocultas	*{ IfcColumn }*	
Hidden Lines	*{ IfcColumn }*	
Location Lines	*{ IfcColumn }*	
Rigid Links	*{ IfcColumn }*	
Stick Symbols	*{ IfcColumn }*	
Structural Connections	Not Exported	
Hidden Lines	Not Exported	
Structural Fabric Areas	IfcGroup	
Boundary	*{ IfcGroup }*	
Structural Fabric Reinforceme	IfcReinforcementMesh	
Boundary	*{ IfcReinforcementMesh }*	
Fabric Wire	*{ IfcReinforcementMesh }*	
Structural Foundation Tags	Not Exported	
Structural Foundations	IfcFooting	
Hidden Lines	*{ IfcFooting }*	
Repr. plano	*{ IfcFooting }*	
Structural Framing	IfcBuildingElementProxy	

Figure 2.12: IFC export settings interface in Revit 2017.

One of the problems identified here is that not all users of the tools are entirely familiar with the implications in the data exchange through the IFC format, and much less with the technical aspects related to the mapping concept and the meaning associated with each IFC entity. Sometimes, due to this lack of knowledge, or because there is no possible correspondence between the entities of both data structures, some parts of the information about the exported model remain undefined. When this occurs, these entities are exported under the category "ifcBuildingElementProxy", an IFC entity used as a wild card since it does not provide any associated meaning. Problems like this and challenges related to the use of IFC are analysed and documented in the next section.

One of the most common limitations associated with the use of standards based on data schemas lies in the incapacity to represent the meaning of any information that is not defined in the schema. To try to overcome this problem, some standards turn to extension mechanisms to facilitate the definition of additional information. In the case of IFC, one of the mechanisms for this dynamic extension is the IFC Property Set (Pset) (Figure 2.13). These properties allow users to specify alphanumeric information and add them to entities that represent components or parts of a building, for example to add more information about some of their features.

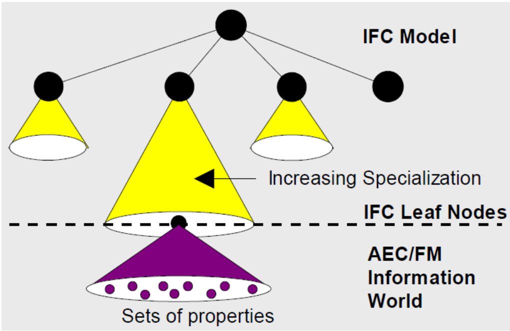

Figure 2.13: Limits of the IFC schema (Liebich & Wix, 2000).

IFC Property Sets can be classified into two groups: (1) property sets standardized by buildingSMART (e.g., Pset_BeamCommon) and (2) non-standardized property sets, which can be created and added by the users. The names of property sets start with the prefix "Pset_" (e.g., Pset_RoofCommon), as shown in Figure 2.14.

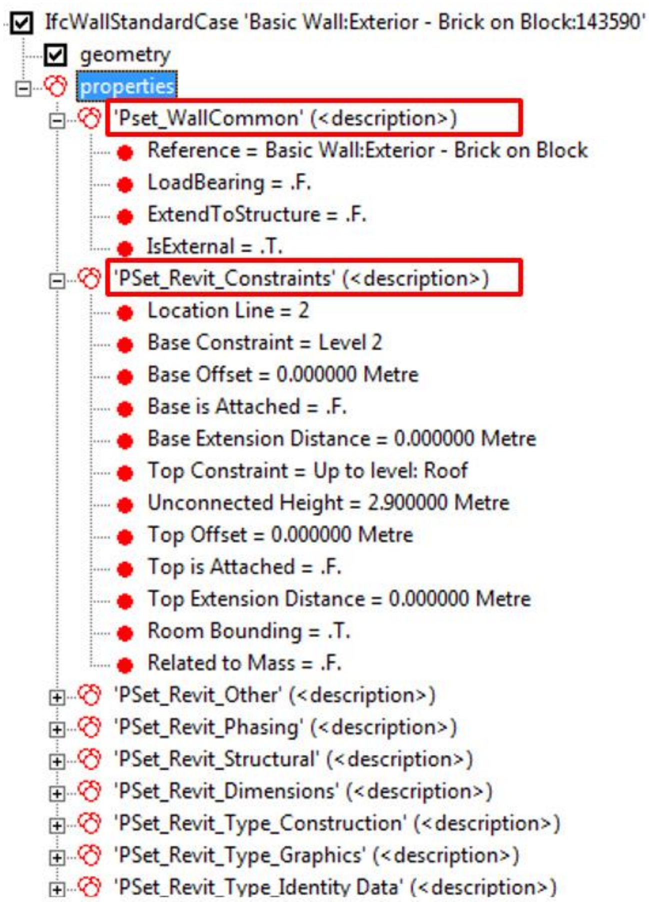

Figure 2.14: Example of Property Sets defined in an IFC model.

2.4.2. Problems and challenges using IFC

The main problem in creating a standard for interoperability between AEC software applications, such as IFC, lies in the impossibility of capturing all the features of the building model without losing any essential meaning. As discussed above (Section 2.2.2), this problem is difficult to overcome because each authoring tool uses its own set of rules to describe the virtual representation of the building. For example, Revit and Archicad provide different representations for the same type of components in the digital building model. Differences in the representation can be found, for example, in the number of layers used to describe them. Moreover, they provide different solutions to resolve the encounters between components, for example walls (see Figure 2.15).

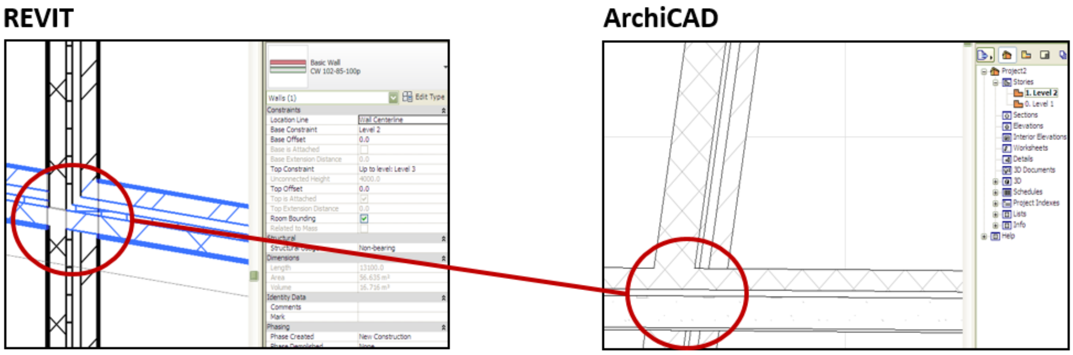

Figure 2.15: Different solutions to solve the intersection of walls in Revit and Archicad.

The non-correspondence between representations of native components makes it difficult to exchange them from one system to another. As a result, they typically end up being exported as neutral geometric objects. Kiviniemi et al. (2005) claim that part of the problems in this exchange are due to the medium used: a file. As an alternative, they proposed the creation of standardized application interfaces for each domain, built on the IFC standard, through a client-service model. However, a decade later, this approach does not seem to have been adopted by the industry. In conclusion, it is difficult to develop alternatives and standards capable of dealing with these divergences in the representation methods. This is even more difficult when considering that programs, and the corresponding internal data structures, are more frequently updated to new versions (usually yearly) compared to standards such as the IFC.

From the point of view of the practical use of IFC, various associated problems and shortcomings have been identified over the years. For example, information is lost in the exchange; it is not interpreted correctly and needs to be remodelled; and there is a lack of rules and restrictions for change propagation. Another problem arises when the size of exchanging IFC files makes it difficult for them to be loaded within authoring tools. This is often due to the limited hardware of computers (most of the time in terms of RAM memory) and the limited capability of the tools to process and internally manage a maximum number of objects. Solutions to these problems usually require the building model to be divided into smaller parts.

Other limitations of IFC are related to the lack of mechanisms for grouping objects or labelling representations (e.g., to assign a level of detail), as well as to provide representations of the BIM model tailored to the particular needs of each discipline. For example, while architects may require a representation based on the dimensions, materials and textures of components, structural engineers may require representations based on analytical models, and so on.

Limitations in data exchange using IFC, such as those discussed above, have led buildingSMART to propose strategies to overcome them. To this end, four standards have been developed to provide support to IFC in different aspects: (1) Model View Definitions

(MVD) to support requirements, (2) Information Delivery Manual (IDM) to support processes, (3) buildingSMART Data Dictionaries (bSDD) to support the mapping of terms, and (4) BIM Collaboration Format (BCF) to support the coordination and management. These standards are considered the core components of the buildingSMART technology. Moreover, there are other open standards such as Construction Operations Building Information Exchange (COBie) and Product Data Templates (PDT) that are being adopted in countries like the United States and the United Kingdom. These standards are described below.

2.4.3. Model View Definitions (MVD)

The purpose of Model View Definitions[49] is to facilitate data exchange through the IFC standard (including geometry and non-geometry data) by generating a view of the data which is specific to the needs of those who will use the information. Carrying out the specification of these requirements manually is complex and cumbersome. To facilitate this task, there is a set of MVDs specified as legal subsets of the IFC schema according to general use cases or purposes. For example, in an MVD addressed to meet the needs for visualization, the geometry of the BIM model is exported as "Boundary Representations" (BRep)[50], while in an MVD addressed to meet the needs for coordination (e.g., clash detection, location of components), part of the geometry is parameterized. Some examples are illustrated in Figure 2.16.

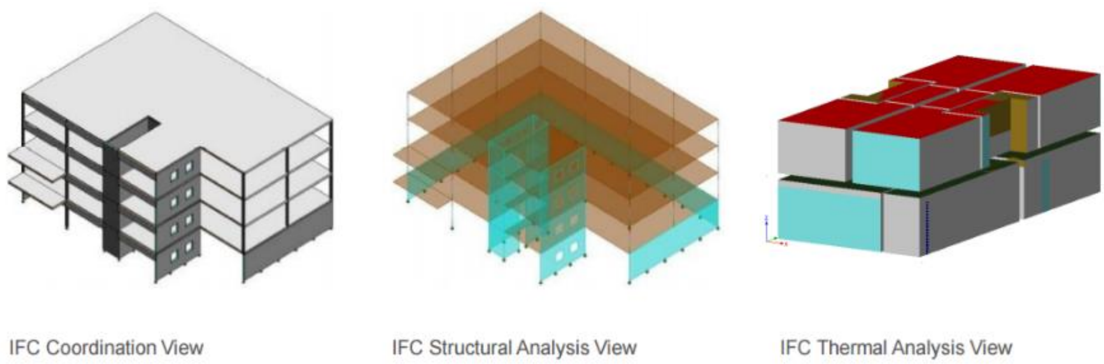

Figure 2.16: Example of different model view definitions (Liebich, 2014).

In recent years, buildingSMART has developed a set of MVDs for different versions of the IFC standard which are known as official buildingSMART model view definitions. Among them, the "Coordination View" was the first MVD implemented to facilitate the coordination among the disciplines involved in a building project: architectural, structural and mechanical. This coordination is mainly done at geometry level. A new version was

[49] The concept of MVD was originally introduced by Hietanen in 2006 to define the scope and details of IFC implementations.

[50] Boundary Representation (BRep) is a method used in solid modelling for representing the shapes using the limits. Namely, information about solids is represented through basic topology elements (faces, edges, and vertices). This representation is usually compared with the constructive solid geometry (CSG) representation, which is based on the representation of solids using primitives and through Boolean operations between them.

released later with the name "Coordination View V2.0" (abbreviated as CV V2.0). This was developed for the IFC2x3 schema, while "Reference IFC4 View version 1.0" (abbreviated as RV IFC4 V1.0) was developed for the IFC4 schema.

Other MVDs have been designed to support data exchange for other purposes. For example, the BLIS Consortium developed an MVD to support an exchange from structural building information models to structural analysis in 2007, though this is no longer maintained (Ramaji & Memari, 2016). In this case, the information about the model needs to be represented as simple lines for linear elements and dots for junctions or connected nodes, as this is essentially what is required to perform the calculation of the building structure. A connection of components represented by topological representation (basically, lines and dots) provided in a Structural View, or by means of faces of their corresponding boundaries provided in a Coordination View, are two clear examples where the geometry needs to be represented differently according to each purpose. For more advanced stages of the building lifecycle, the "FM Basic Handover" MVD was developed to define the general requirements for facility management.

Two other MVDs that derive from the IFC2x3 Coordination View V2.0 that have been developed for IF4 are: "IFC4 Reference View" (RV) and "IFC4 Design Transfer View" (DTV). The differences between these two MVDs and the associated uses are described in Figure 2.17 and in the BuildingSMART website specified for the IFC4 implementation.

Comparison of the objectives and target workflows	
IFC4 Reference View (RV)	**IFC4 Design Transfer View (DTV)**
Goals	
▪ satisfy the referencing workflow, i.e. the result of the import is "read-only" (not modifiable)	▪ satisfy the handover work flow, i.e. import for further editing (import into native elements)
Scenario includes	
▪ background reference ▪ clash detection ▪ any viewer-based work flow	▪ takeover architecture in structural ▪ import spaces into MEP ▪ takeover a previous design
Expected user experience	
▪ ownership remains with the sender ▪ frequent updates ▪ fast export/import times ▪ 100% validity, no rework expected	▪ ownership handed over to receiver ▪ low frequency, sometimes "one of" ▪ longer export/import time tolerable ▪ some rework accepted, if limitations well known

Figure 2.17: Table comparing the use of IFC as a reference view or as a design transfer view[51].

[51] BuildingSMART (2015). Retrieved from http://www.buildingsmart-tech.org/specifications/ifc-view-definition/ifc4-reference-view/comparison-rv-dtv/.

The “IFC4 Reference View” is used in workflows where the information of the model to be exchanged is not expected to be edited. This could be the case for BIM models that need to be combined with others for checking (e.g., clash detection). The “IFC4 Reference View” also allows agents involved in a project to maintain their limit of responsibility on the information of the model to be transferred to others.

The “IFC4 Design Transfer View” is used when there is an intention to reuse the information of the model, for example, to continue with the development of the design. An example can be found in the workflow between an architect and a structural engineer. The structural calculation can lead to changes in the arrangement of structural components in the model, which in turn have their effects on the architectural model as well. The “IFC4 Design Transfer View” allows the structural engineer to edit the information of the model to perform the calculations. However, it is not clear to what extent the information transferred and edited can then be integrated into the original architectural model using the IFC standard. According to buildingSMART, “round-trip” data exchange scenarios are not supported through the MVD mechanism.

2.4.4. Information Delivery Manual (IDM)

The Information Delivery Manual (IDM) is an ISO standard (ISO 29481-1) currently supported by buildingSMART. Its purpose is to help members of a project team to define agreements on the processes and the data required by BIM, as well as responsibilities they have in them. It includes the information that each participant in the project should provide (exchange) in each part of the development (process). The specification of the data requirements involves at least two types of software applications in which information needs to be exchanged between them.

The IDM was introduced in the context of the BLIS (Building Lifecycle Interoperable Software)[52] project in 2000. Later, the specification was introduced as an official component of IFC standardization in 2007 (Wix, 2007).

From an integrated approach with other buildingSMART standards, these specifications are provided through four main deliverables: process maps, exchange requirements, exchange requirements according to IFC concepts and a generic guide about objects and data of the BIM model to be exchanged (See, Karlshoej, & Daves, 2011). This way, while the purpose of the IDM is to capture processes and data exchange requirements (involves capturing knowledge from domain experts), the purpose of the MVD is aimed at mapping these exchange requirements to the IFC schema (involves software implementation) (See et al., 2011).

2.4.5. BuildingSMART Data Dictionaries (bSDD)

To continue developing a standardization framework for AEC industry, buildingSMART has provided a Data Dictionary (bSDD) focused on the meaning of information that is

[52] BLIS project. Retrieved from http://www.blis-project.org/.

exchanged. This way the bSDD, which relies on International Framework for Dictionaries (IFD), is another of the three core components of the buildingSMART technology and ISO based ontology (ISO 12006-3:2007, 2007) intended for the integration of a large number of concepts about building products. This initiative is the result of two previous projects: BARBi (Bell & Bjørkhaug, 2006) and LexiCon (Woestenenk, 2002).

In the bSDD, concepts are defined and identified with a number (e.g., #12345) in an object data library available in the cloud[53], which can be accessed by manufacturers and BIM users. From this library, manufacturers can define relations between parameters of their products and concepts available in it with the same meaning, and include these relations in the information available about their products. These relations can also be specified in the product database of the bSDD, making it possible for third parties to find these products through this relationship.

For example, a window manufacturer can define a relation between the "width" of their window products and the corresponding parameter defined in the library (e.g., IFD#12345 = "width"). Later, a designer may require a window for the design of a building. In the representation of this window in the BIM authoring tool, he can assign the name of the parameter used to define the width of the window to the corresponding concept available in the object data library (e.g., IFD#12345 = 80 cm). Through this link, the designer can search for all window products available on the product database of bSDD whose limits include the value specified in the width parameter (80 cm). For a successful use of bSDD, the product database should be constantly updated and it should provide a minimum critical mass of products.

2.4.6. The BIM Collaboration Format (BCF)

Another open standard intended for the coordination of BIM-based projects is the BIM Collaboration Format (BCF). This format is useful when project managers need to communicate possible inconsistencies and conflicts encountered in models (e.g., elements that overlap, the detection of spatial conflicts, incorrect assembly, etc.) provided in a visual form. In many aspects, BCF replaces the old practice of taking screenshots to capture a view of the model in visualization or design applications, editing them by using tools like Photoshop, or similar, marking with circles and arrows what is wrong in the model, and sending these images back to the author of the model with the intention of correcting these errors.

BCF was created with the aim of avoiding this cumbersome process by providing a standardized mechanism based on an open XML file format. This format enables information to be provided about different screenshots of the BIM models, including

[53] There are various alternatives to access the bsDD. One example is through a REST API available on the Web which provides different access methods. Retrieved from http://bsdd.buildingsmart.org/docs/rest.html.

overlapped comments. As a result, these views may be updated directly in the modelling applications used by the creators of these models.

Figure 2.18 shows an example in which the BCF format is used for exchanging comments and screenshots related to clash detection problems in the pre-construction stage of a building project. In this case, the exchange is performed between the BIM team and the technical office, both hired by the general contractor. This project was developed as a solution to provide a sanitation facility for a sports centre. The example shows a report generated as a result of the clash detection between structural and sanitation systems.

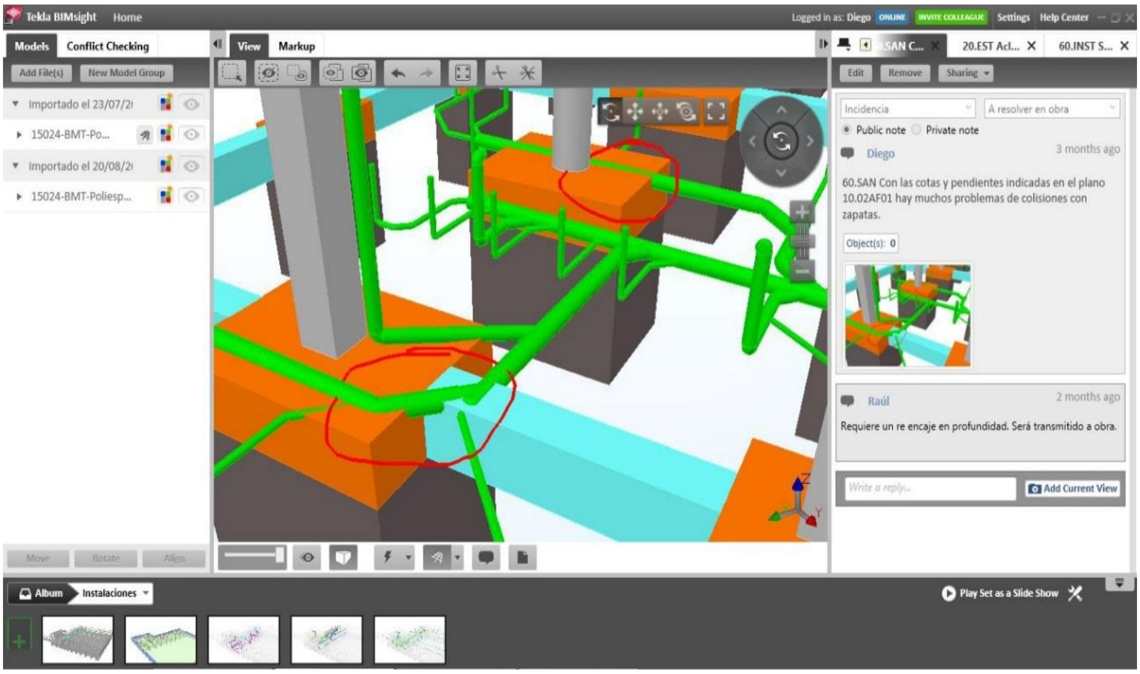

Figure 2.18: Managing clash detection conflicts in Tekla BIMsight using BCF (courtesy of Diego Vidoni, Bimetric Lab).

2.4.7. Construction Operations Building Information Exchange (COBie)

COBie is mainly used as a spreadsheet data format[54] to deliver the information about a BIM model that is necessary for the operation and maintenance of the building. This specification was originally developed by Bill East, while he was in the United States Army Corps of Engineers (2007), in order to develop an Asset Management Framework (AMF) to manage the civil infrastructure assets (East, 2007; Hale, Woolridge, & Stogner, 2008). As an asset management handover document, COBie is generated by the project team and then delivered to the owner.

The gap filled by COBie can be found in the needs of some recipients (e.g., civil servants) who need to identify and analyse all the non-geometric information about a building as plainly as possible. In COBie spreadsheets, information about the BIM model is organized in a simple way into different categories. These categories enable specification

[54] Other formats are STEP-Part 21 and ifcXML.

of equipment lists, features of the spaces, product data sheets and so on. Because of this simple organization, it should be easier to check and search for specific data.

There are different versions of COBie adapted according to each need. For example, the United Kingdom has developed their own version of a COBie template (COBie-UK-2012) adapted for the public procurement projects in this country.

2.4.8. Product Data Templates (PDT)

Following an approach similar to that of COBie, Product Data Templates are also spreadsheets to describe properties about building products. As in the case of COBie, information about the geometry of products is not included in these templates. The PDT specification was created by the Chartered Institution of Building Services Engineers (CIBSE)[55] from the need to work according to BIM Maturity Level 2 in the United Kingdom. By working at this level, BIM users face the difficulty of having to collect product information scattered in different data sources and product catalogues, and asking manufacturers for specific information required in the project. In order to avoid this inefficient process, the use of standardized product data templates (PDT) in the form of spreadsheets (Figure 2.19) was proposed by this institution.

In these templates, information is specified according to five columns: category, name of parameter, value, unit and description. The parameters are grouped in two main blocks. The first block contains intrinsic information about the product (general description, contact, construction, performance, electrical, sustainability and maintenance). The second block contains information about the product according to the project (application, performance, dimensions and controls).

[55] The Chartered Institution of Building Services Engineers (CIBSE). Retrieved from http://www.cibse.org/.

Template Category	Air Grille/Diffuser			
Template Version	v1			
Category Description	Supply and extract air terminals (excluding external louvres & transfer grilles)			
Classification System				
Classification	Value			
Suitability for use	Approved			
Template Custodian	CIBSE			
Information Category	Parameter Name	Value	Units	Notes
	Manufacturer Data			
Specifications	Manufacturer		Text	
Specifications	Manufacturer Website		URL	
Specifications	Product Range		Text	
Specifications	Product Model Number		Text	or code
Specifications	CE Approval		Text	number, yes, no
Specifications	Product Literature		URL	
Specifications	Features		Text	Free text to describe product
	Construction Data			
Specifications	Face Type		Enumeration	
Specifications	Shape		Enumeration	
Specifications	Trim		Enumeration	
Specifications	Trim Material		Text	e.g. Aluminium, Galvanised MS Steel, Stainless Steel, Plastic, etc.
Specifications	Trim Finish		Enumeration	
Specifications	Trim Colour		Text	e.g. Natural (Self-finish), or Colour(s) & RAL(s)
Specifications	Core Type		Enumeration	
Specifications	Core Material		Text	e.g. Aluminium, Galvanised MS Steel, Stainless Steel, Plastic, etc.
Specifications	Core Finish		Enumeration	
Specifications	Core Color		Text	e.g. Natural (Self-finish), or Colour(s) & RAL(s)
Specifications	Removable Core		Y/N	
Specifications	Integral Plenum	Y	Y/N	
Specifications	Integral Plenum Material		Text	e.g. Aluminium, Galvanised MS Steel, Stainless Steel, etc.
Specifications	Integral Volume Control Damper	Y	Y/N	
Specifications	Integral Volume Control Damper Type		Text	
Specifications	Integral Volume Control Damper Material		Text	e.g. Aluminium, Galvanised MS Steel, Stainless Steel, Plastic, etc.
Specifications	Integral Fire Damper	Y	Y/N	
Specifications	Fire Rating		Minutes	e.g. 60 minutes, 120 minutes
	Accessories Data			
Specifications	Volume Control Damper	Y	Y/N	
Specifications	Fire Damper		Y/N	
Specifications	Intumescent Block		Y/N	
Specifications	Plenum		Y/N	
Specifications	Blanking Plates		Y/N	
Specifications	Concealed Fixings		Y/N	
Specifications	Rear Deflection Blades		Y/N	

Figure 2.19: Example of a part of a product data templates for air heaters (CIBSE, 2015).

The aim of using PDT templates is to standardize the current disparate information about building products. The specification of these templates was generated through questionnaires where manufacturers were asked about the necessary data of their products required in Level 2 BIM projects. Once templates were created for each type of product, these templates were provided as Product Data Sheets to the corresponding manufacturers, according to each type, so that they could fill in the third column (value) with the corresponding data of their products.

The main users of PDT are general contractors and facility managers. Therefore, most of the parameters specified in these templates provide information intended to allow assessment of the performance of the components. These parameters also include the information necessary to carry out their operation and maintenance. An example of the utility of PDT is when a component is broken or becomes obsolete and needs to be replaced by a new one. The information provided in a PDT should facilitate finding the most suitable substitute component by comparing their characteristics through the parameter values.

2.5. Summary and conclusion

The application of BIM methodology in the building AEC industry has a lot of advantages, but also a number of drawbacks, many of them related to the use and exchange of information. This chapter has presented a brief overview of the main issues related to this use and exchange of information analysed in the work processes involved in the different stages of the building life cycle (Figure 2.20). As a result of this analysis, some barriers, limitations and shortcomings were found that are currently leading to different inefficiencies, especially in the development of BIM-based projects.

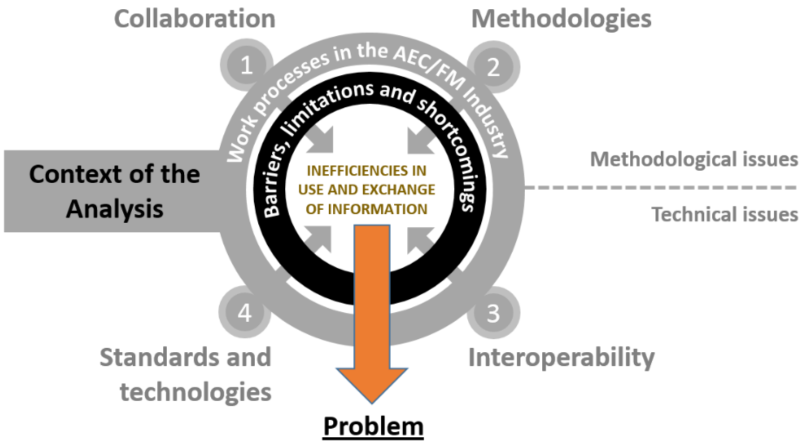

Figure 2.20: Methodology used to analyse the inefficiencies in BIM-based projects.

The inefficiencies documented in this chapter, investigated in four domains – (1) collaboration, (2) methodologies, (3) interoperability and (4) standards and technologies – have been identified based on the experience gained with various collaborations in research projects and the review of the literature on related topics, leading to the following causes as the main reasons for them:

- Collaboration between agents is limited to a short-term approach (limited to the life of a project), where the relationship between the agents does not have to be maintained after the end of the project.
- There is some difficulty in providing continuous flows of information between work processes in the development of building projects. This situation often leads to an overload in coordination every time information about the BIM model needs to be exchanged.
- Resolving the interoperability problems is not the top priority for most software developers of BIM applications.
- Related to the above, some software vendors are not interested in providing open interoperability because this is not aligned with their business strategies (e.g., providing all the necessary tools through the same proprietary format).
- Immaturity in the use of BIM technologies. The AEC industry must continue training to reach a higher level of maturity in the use of BIM technologies to be able to get all the benefits that are expected in more efficient developments of building projects.
- Resistance to change is still present in some parts of the industry. Agents prefer to choose known methods and those with greater control (e.g., spreadsheets) as a means of exchanging data, even when they are less efficient (e.g., buildingSMART standards and technologies). New mechanisms that facilitate the management of the latter, as well as greater involvement of software vendors for their implementation, are needed to reverse this situation.

- There is a lack of mechanisms to extend the capabilities of current interoperability standards.

The barriers that are leading to some of these inefficiencies have also been analysed in different contexts with the following conclusions:

1. **Public bidding BIM-based projects.** Public administrations in many countries do not clearly know what they need for the delivery of BIM-based projects in public bidding: what information, in what format and for what purpose. In Europe, countries such as the UK and the Nordic countries have taken the initiative in elaborating data requirements for the delivery of BIM-based projects, while in other countries like Spain this process has just started. The limited investment made by some governments is also seen as a barrier in these countries. In many cases, this is due to a lack of awareness about the benefits of BIM. Although the MacLeamy's curve clearly shows that most benefits arrive in the construction and following stages of the building life cycle (maintenance and disassembly), a greater economic investment is necessary in the design stages. Today, many administrations are still unclear about these benefits, and unwilling to bear this cost.
2. **Software.** BIM authoring tools are becoming very complex pieces of software produced by a small group of companies (e.g., Autodesk, Nemetschek, GraphiSoft, Bentley and Trimble). Since most of them have been designed as solutions for global use, they do not cover those aspects of modelling that are specific to each country: the ways of working and cultural, legislative and methodological factors, and so on. This situation leads to the need for specialized software to be used, typically developed by local companies that are familiar with the above aspects. Since these tools are more designed for calculation and simulation operations rather than for BIM modelling, interoperability in the current BIM-based projects is necessary, at least, between these two types of applications.
3. **Methodologies, standards and workflows.** A large number of specifications and guidelines have been developed in recent years to help manage BIM information. However, their use is limited by the scalability and scope, which are not always clear. Some of them are created according to the needs and idiosyncrasies of specific countries, so that they cannot be simply be adopted or deployed in others. It is difficult to include these local conditions in specifications and guidelines to be used at international level. Even when these are developed at national level, it is difficult for the task groups responsible for their generation to be aware of all aspects related to: the diversity of profiles of companies operating in the sector, the variety of project types, how workflows are carried out on a small scale and so on. To some extent, all these problems are also present when designing standards such as IFC. In Section 2.4, we saw that some strategies to address the lack of interoperability focus on reducing the dimension of the problem to a smaller scale through a standardization of the data requirements associated with common data exchange scenarios (e.g., transferring information from architects to structural engineers). Standards such as IDM, MVD and bSDD are the clearest examples of mechanisms designed to facilitate this sort of exchange. However,

they are not enough to meet all the data requirements that need to be addressed in the data exchange scenarios of a project. An intermediate level seems to be missing here that allows users to easily adapt the requirements of these standardized scenarios to their own needs. Moreover, there may be data exchange scenarios that are not covered by these standards when these are very specific.

From the above conclusions, it becomes clear that some of the inefficiencies encountered are rooted in how the industry currently operates. This involves factors such as experience, culture, business issues, training of practitioners, aims for continuous improvement, etc. These inefficiencies seem difficult to address unless carried out through global solutions or in a joint effort involving the whole sector, which is rather unlikely. However, other inefficiencies encountered, which are more related to technical issues, can be addressed through new technological solutions.

In the next chapter, we will examine the use of Semantic Web technologies as an alternative to providing more adequate support for the data exchange and the facilitation of data. Among other advantages, these technologies enable the explicit and unambiguous definition of information and provide mechanisms to facilitate its automated interpretation by machines. The ability to interpret information is essential to automate data exchange so that users can save time by reusing BIM models as well as information from other sources, such as product catalogues.

3

Application of Semantic Web technologies to reuse and share building information

In Chapter 2 we have analysed the inefficiencies in the use and exchange of information during the different stages of the building life cycle, particularly within the context of BIM. We concluded that some of these inefficiencies are due to the difficulty for people and tools to interpret and efficiently process shared information. We have suggested that a greater support to overcome these inefficiencies can be provided through the use of Semantic Web technologies. In this chapter, we review the methods and techniques from the field of Semantic Web and ontology engineering in light of their capabilities to: (1) explicitly and unambiguously define information and (2) to integrate data from different sources and domains. The first part of this chapter reviews the fundamental concepts underlying the Semantic Web technologies and the linked data approach, how these technologies are applied for knowledge representation of building information, and what the state is of the research in this field. In the next part of the chapter we examine data integration methods based on these technologies and their application to facilitate interoperability and to integrate information related to building components and products. The chapter ends with a discussion about the benefits that can be achieved through the data integration methods analysed in the literature review, including research projects carried out in the AEC industry.

3.1. Knowledge representation

This section introduces the fundamentals of Semantic Web technologies, how they are applied for data integration and knowledge representation, and how this knowledge is represented through ontologies. It starts with a brief introduction to the concepts of data, information and knowledge as the three key components of a knowledge system (Thierauf, 1999). The definition of these concepts is limited and adapted to the understanding that is required in the following sections of this document.

3.1.1. Data, information and knowledge

The meaning of the concepts of data, information and knowledge is often presented as ambiguous, leading people to refer to them interchangeably. Hence, it is necessary to provide a definition for each of them.

- **Data.** Different definitions of the concept of data have been formulated. According to the Cambridge Dictionary[56], data can be defined as "information, especially facts or numbers, collected to be examined and considered and used to help decision-making, or information in an electronic form that can be stored and used by a computer". Similar definitions are provided by other authors which consider data as a description of facts that can be processed by a system to produce an output (Gregor & Hart, 2007; Maddison, 1989; Martin & Powell, 1992; among others). However, most of these authors agree that it is difficult to provide a precise and generally accepted definition of data, in the same way that it is difficult to explain the difference between data and information (Gray, 2003; Stenmark, 2001).
- **Information.** The concept of information has also been defined in many different ways. In general terms, it can be considered as the data required to solve the uncertainty of a question. Also, information can be defined as a result of data aggregation. However, different meanings of this concept can be found in the literature depending on the context, the field and the author, as well as on how the term data is defined. A commonly accepted demarcation criteria between data and information is that the second has a purpose: to provide information to someone in a given context. In the field of communication systems, one of the most important references is Claude Elwood Shannon, who is considered the founder of the information theory field. In the article "A Mathematical Theory of Communication" (1949), Shannon and Weaver define information as "a purely quantitative measure of communicative exchanges". Over the years, information theory has been expanded from the mathematics and electrical-electronic engineering area towards other disciplines such as computer science and natural language processing.
- **Knowledge.** It can be defined as the result of information transformed into meaning. Polanyi (1966) claimed that knowledge can be divided into tacit and explicit. While the former refers to things that people know implicitly and cannot express, the latter refers to knowledge that can be made explicit by defining statements, rules and procedures (Davies, 2015). This way, while tacit knowledge is in the nature and in the memory of people, explicit knowledge can be used by information systems (Sanchez, 2004). In the world of computation, the meaning is obtained when the information is processed by interpreters (Mingers, 1995). However, knowledge can also be described through logic formalisms to facilitate

[56] Collins Dictionary. Retrieved from http://dictionary.cambridge.org/dictionary/english/data/.

its processing. Knowledge representation is defined by John F. Sowa as "the application of logic and ontology to the task of constructing computable models for some domain" (Sowa, 1999).

All these three concepts – data, information and knowledge – are the components of a knowledge system and also the basis of Knowledge Representation (KR), a branch of artificial intelligence aimed at representing structured information about a domain that includes the principles of logic to automate reasoning and facilitates the creation of new knowledge. This is achieved by defining syntaxes capable of making the information readable by machines, thereby providing access to elements that enable knowledge to be inferred (Stroka, 2005).

With the World Wide Web (WWW) becoming a huge repository of data accessible from everywhere, new opportunities have appeared for knowledge representation. On the WWW, knowledge can be provided as interlinked content described in natural language. Applications using techniques and technologies based on natural language processing (NLP), for example, can be applied in automatically processing and analysing the unstructured textual data in this huge interlinked repository (Popowich, 2005). Semantic Web technologies follow an alternative approach by complementing the information that can be provided on the Web with explicit semantics based on formal knowledge representations as provided by ontologies.

3.1.2. Ontologies

The term "ontology" has its origin in philosophy, although its meaning varies depending on the community and the application field. In general, ontologies are intended to describe some kind of knowledge by developing a system of universal categories and their intrinsic relationships (Sack, 2013). Different authors have provided definitions of this term adapted to the context of computer science and knowledge engineering. In this thesis, we will take the meaning provided by Gruber (1993), which defines an ontology as "a formal and explicit specification of a shared conceptualisation of a domain of interest". In this definition, "formal" means that the ontology follows agreed rules (formalisms) that allow it to be used widely, "explicit" means that the meaning of its concepts is defined explicitly through the type, relations and constraints, and "shared conceptualization" refers to a conceptualization that is shared between different parties (Corcho, 2005; Guarino, Oberle, & Staab, 2009).

Ontologies can be represented using a wide variety of languages. These languages provide different formalisms to describe classes, relations, functions, formal axioms and individuals (Corcho, 2005). Classes represent abstract or specific concepts that are described by properties (so-called "roles" or "slots"). Classes in ontologies are usually organized into taxonomies, enabling their classification in a hierarchical form. This classification, in turn, restricts their intended use to describe an instance in the domain of the ontology. Relations define a type of association to indicate how classes and individuals are related to one another. Formal axioms – prepositions that are taken to be true – are generally used to define that part of knowledge that can be formally defined through the above components. A formalization based on axioms provides semantic information that enables new knowledge to be inferred from given facts (explicit data such as relations) in the ontology. This is why ontologies are useful to facilitate automatic reasoning – derivation of facts that are not explicitly expressed in the ontology. Moreover, inference rules can be provided separately from the ontology. Rule languages designed for the Semantic Web enable to describe additional relations that cannot be provided in the ontologies. Finally, individuals are instances of concepts that represent occurrences that exist in reality according to the application domain. Ontologies and individuals – as instances of their classes – constitute a knowledge base.

There are different reasons to develop ontologies. According to Noy and McGuinness, (2001), they can be developed for (1) sharing a common understanding of the structure of information among people or software agents, (2) reusing a domain of knowledge, (3) making explicit domain assumptions, (4) separating domain knowledge from operational knowledge, and (5) analysing a knowledge domain. Ontologies can also be classified according to the degree of abstraction and the field of application as (1) *upper ontologies* (or top-level ontologies), used to represent general and common concepts on a higher level, (2) *domain ontologies*, used to describe fundamental concepts according to a specific domain of interest, (3) *task ontologies*, used to describe the components and relations according to a general activity or task, and (4) *application ontologies*, used for a specific use or task.

Ontologies can be created using different methodologies (KACTUS[57], METHONTOLOGY[58], On-To-Knowledge[59], HOLSAPPLE[60], DILIGENT[61], HCOME[62] and others). These methodologies, most of which emerged in the 1990s, enable users to create ontologies from scratch.

One of the most complex issues related to the use of ontologies is that their character of shared conceptualization is often subjected to a constant evolution over time. If the ontologies are required to maintain the pace of this constant evolution, a high maintenance cost emerges, not only in the maintenance of the ontologies themselves but also in the

[57] KACTUS is a European ESPRIT project (1996) aimed at enhancing the reuse of knowledge in the CIME area by developing standards for the reuse of knowledge and by providing reusable ontologies in different application areas.
[58] METHONTOLOGY is a well-structured methodology and life cycle definition for developing ontologies from scratch developed by Fernández, Gómez-Pérez, and Juristo (1997).
[59] On-To-Knowledge is an ontology-based tool environment designed to speed up knowledge management, dealing with the large numbers of heterogeneous, distributed, and semi-structured documents on the Web, and developed by (Fensel et al., 2000).
[60] HOLSAPPLE is a methodology based on a collaborative approach to ontology design divided into four phases: Preparation, Anchoring, Iterative Improvement and Application. It was developed by Holsapple and Joshi (2002).
[61] DILIGENT is a methodology intended to support domain experts in a distributed setting to engineer and develop ontologies with the help of a fine-grained methodological approach based on Rhetorical Structure Theory (RST), developed by Pinto, Staab, and Tempich (2004).
[62] Human-Centered Ontology Engineering Methodology (HCOME) is a methodology developed by Kotis, Vouros, and Alonso (2005) for the development and evaluation of living ontologies addressed to communities of knowledge workers. The methodology is supported by HCONE (Human-Centered ONtology Engineering Environment).

maintenance of the applications that use them. Methodologies to design ontologies such as those mentioned above are addressed primarily to ontology engineers and experts. This is a barrier when end-users (e.g., specialists, stakeholders and experts in a knowledge domain) want (or need) to define an ontology by themselves. Although different tools (Protégé, Top Braid Composer, Neon Toolkit, OilEd, etc.) can be used to create ontologies and modify them, this process still requires a minimum of knowledge of ontology engineering. For that reason, it is necessary to provide easier-to-use ontology prototyping methods and mechanisms in order to allow end-users to carry out these tasks through social and highly participative approaches (De Nicola & Missikoff, 2016).

3.1.3. Types of representation

In the domain of knowledge representation there are various types of specifications for representing information and knowledge: vocabularies, thesauri and taxonomies. These can be used according to the expressiveness that is required for each case. In order to facilitate a clearer understanding of these terms, what the difference is between them and what their relation is to the term "ontology", Lassila and McGuinness (2001) provided a classification to help visualize these terms within a linear spectrum from less to more expressivity according to their capacity to represent the information.

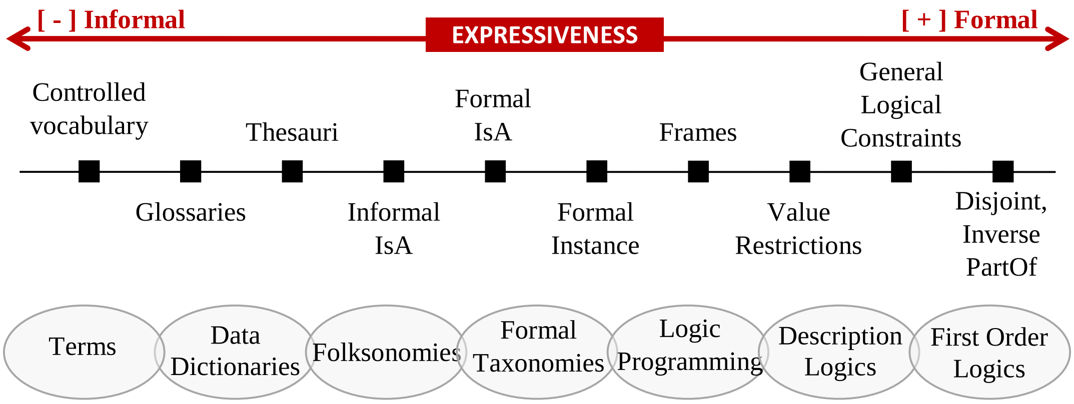

Figure 3.1: Classification of ontologies according to their level of formalization (Lassila & McGuinness, 2001).

Starting from the left part of this classification – the more informal one – a "controlled vocabulary" is defined as a finite list of terms; a "glossary" is defined as a controlled vocabulary including an informal definition of its semantics in natural language; a "thesaurus" is defined as a controlled vocabulary that includes additional semantics defining how the concepts are connected; an "informal IsA hierarchy" is an explicit hierarchy of classes, where subclass relations are not strict (a class can have one or more superclasses); in "formal IsA hierarchies" these relations are strict, so a class can only be a subclass of one other class (Sack, 2013). A "formal instance" is a formal IsA hierarchy in which relations can also be instantiated (Lassila & McGuinness, 2001). The latter three types of hierarchies (informal IsA hierarchy, formal IsA hierarchy and formal instance) are also called "taxonomies". The term "taxonomy" comes from the Greek words "ταξις" (order) and "νομος" (law, rule), which in this case refers to classifications based on the categorization of a set of concepts in a hierarchical structure following a strict set of rules.

Logical constraints can be included in taxonomies in order to express constraints in the relations between concepts, leading to an expressiveness closer to the ontology definition provided above.

All these forms described above produce a certain level of formal inference. While the inference on the left side of the spectrum is limited to a simple form (e.g., inferring that an instance of a class is also an instance of its superclass), the inference on the right side is based on a considerably more complex form (e.g., inferring that a data set is invalid as it does not comply to the constraints in the ontology). As such, all these forms of inference essentially allow new data, information and knowledge to be inferred depending on expressiveness.

3.1.4. Application examples

In the last few decades, the development of dictionaries, classifications, controlled vocabularies, taxonomies and ontologies has been the focus of many research projects and initiatives[63] addressed in the field of the AEC industry. Among them, the definition of controlled vocabularies, generated as a result of consensus among different agents of the sector, is especially relevant for different fields of activities (e.g., providing a method for effective exchange of information). As in other industries, these vocabularies are used to define the basis for setting the semantics of information for specific domains ("the shared conceptualization").

The most effective efforts in providing controlled vocabularies have been carried out through the specification of standard classifications – as described in Section 2.3.7 of Chapter 2. Furthermore, efforts in creating more specific vocabularies have been driven by the European Union, as in other continents, through different mechanisms in the research field. For example, in the area around Efficient Buildings Energy Data Models, the effort to reach consensus on controlled vocabularies has been provided through VoCamps (Vocabulary Camps), an initiative of the European Commission carried out with the support of the project ADAPT4EE[64]. However, the utility and practicality of the

[63] For example, the bsDD (buildingSMART Data Dictionaries), currently developed by the buildingSMART consortium, is the result of LexiCon (the Netherlands) and BARBi (Norway) initiatives. While LexiCon is a data reference library developed to create and maintain vocabularies (Woestenenk, 1998, 2000), BARBi is another reference library based on the framework of the ISO 12006-3 intended to provide a specification of the concepts of buildings and their individual parts or products (Bjørkhaug, 2003). Other initiatives and research projects are e-Construct Project, where a bcBuilding definitions taxonomy was developed (Tolman & Böhms, 2002); ICONDA (The International CONstruction Database), a project initiated in the 1980s as a database for the construction industry, where information about planning and building products is facilitated through a multilingual terminology (Fraunhofer IRB, 2011); and the SEMANCO project, where an ontology to be used as mediator for the integration of different data sources related to the energy domain was developed (Nolle, Nemirovski, & Sicilia, 2013).

[64] Adapt4EE is a project aimed at developing and validating a holistic energy performance evaluation framework for buildings that integrates information about the BIM, critical business processes and consequent occupant behaviour patterns, enterprise assets and respective operations, and environmental conditions. Retrieved from http://www.adapt4ee.eu/.

use of controlled vocabularies have been topics of debate and discussion in several publications.

Among other authors, Lima, Zarli, and Storer (2007) analyse the state-of-the-art in the use of controlled vocabularies in the AEC industry field. They claim that the more precision is required on the meaning, the more control has to be provided in the use of terminology. This becomes a difficulty when experts and non-experts have to agree on a common meaning of concepts. The authors present an example in which a stonemason and a cost estimator use different terms to refer to the same thing: a “brick pillar” and a “short length of thick wall made from brick”. They state that in the United Kingdom, this difference is established in the rules that define the dimensions of the elements. The use of these vocabularies is also discussed by these authors in data exchange in building projects. For example, while the components of a BIM model can easily be referenced to manufacturers’ codes, allowing other agents to identify them, other properties of these components also need to be provided through a common vocabulary (dimensions, material, strength and so on), enabling the associated meaning to be identified.

3.2. Semantic Web technologies

The WWW opens up new opportunities for the use of knowledge representation in which formal descriptions of the semantic content of documents provided on the Web can be processed by computational agents (Hendler & van Harmelen, 2008). This publication and the use of semantic data on the Web have come to be known as the *Semantic Web*, conceived as an extension of the current Web. The term was coined in 1998 by Tim Berners-Lee, the inventor of the Web and founder of the W3C (World Wide Web Consortium), with the aim of turning the current Web, dominated by unstructured and semi-structured documents, into a *web of data* (Berners-Lee, 1998). For this purpose, the idea behind the Semantic Web is based on adding semantic metadata to the existing data. A semantic description of the content and its relations in a formal way can be processed by machines. Among the advantages, there is the possibility of reducing human intervention in the processes involved in its interpretation through automated procedures. Providing an explicit meaning of the information is the basis to enabling this automatic interpretation. This is achieved through formally structured and standardized knowledge representations, that is, ontologies.

The use of ontologies comprises two components: (1) a terminological box (TBox), which provides a set of concepts and relations between the concepts necessary to define a domain of discourse, and (2) an assertion box (ABox), which can include a set of instances and relations between them (assertions) according to the concepts and relations defined in the TBox.

An assertion is a statement (or predicate) that is expected to always be true. In the Semantic Web domain, these assertions are expressed through triples, i.e., subject-predicate-object statements that represent facts and relations. More specifically, these statements (triples) consist of two nodes (subject and object) linked by a labelling arc (predicate), representing a logical relationship between the two nodes. For example, in the context of a BIM model representation, the following triple, "Instance:Beam001", "rdf:type" "ifc:ifcBeam", represents the notion: "the object Beam001 is an IfcBeam". These statements can be specified through RDF (Resource Description Framework) (Manola & Miller, 2004), a "*framework for expressing information about resources*" supported by the W3C. Concepts (nodes) in RDF statements can be related to represent information as a directed labelled graph (Hayes, 2004). This way, RDF can be used to relate resources and relations between them (McGuinness & Van Harmelen, 2004).

The Semantic Web includes a set of technologies that have been standardized by the W3C. These technologies are used, as necessary, in the different layers of the Semantic Web architecture[65] to bring semantic data to the WWW (Figure 3.2). The first layer includes the representation of concepts (terms). These are represented by Uniform Resource Identifiers (URIs) which enable a resource on the Web to be uniquely identified. For instance, in the example above, the URI corresponding to the property that relates to the concepts of "Instance:Beam001" and "ifc:ifcBeam" is: http://www.w3.org/1999/02/-22-rdf-syntax-ns#type. In the second layer are the formats to describe semantic metadata, i.e., RDF/XML(Beckett & McBride, 2004), Notation3 (N3)[66] (Berners-Lee & Connolly, 2011) and Turtle (Beckett & Berners-Lee, 2008)[67], among others. RDF/XML, for instance, provides an XML-based serialization syntax for RDF. Turtle and Notation3 are both much more human-readable syntaxes for expressing RDF graphs. Higher layers in the Semantic Web stack include RDFS, OWL, SKOS, SPARQL (Prud'hommeaux & Seaborne, 2008), RIF rules, proofs, trust and so forth. We will limit this thesis to the ontology languages (RDFS, OWL), the query language (SPARQL) and available rule languages (RIF, SWRL, N3Logic).

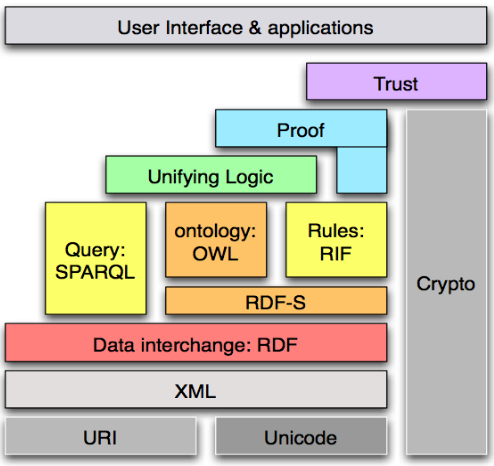

Figure 3.2: Semantic Web technologies stack (Berners-Lee, 2006b).

[65] The Semantic Web layered architecture is also known as the "Semantic Web technologies stack" and Semantic Web Layer Cake.
[66] Notation3 is much more compact and readable than XML/RDF notation.
[67] Terse RDF Triples Language (Turtle) is a concise syntax intended for human readability.

3.2.1. Ontology languages

The next layer of the Semantic Web stack comprises the languages that allow a vocabulary to be represented for describing RDF data, i.e., RDFS (RDF Schema) and OWL (Web Ontology Language), both released in 2004 as a W3C recommendation (orange boxes in the above Figure 3.2). The RDFSis a general-purpose schema language for representing information on the Web (Brickley & Guha, 2004). The expressivity provided by this language is based on basic modelling primitives (classes, subclasses and properties) used to enrich the RDF data model.

The OWL language provides more expressiveness to RDFS by adding advanced constructs and vocabulary along with a formal semantics. This includes new class descriptions as logical combinations of other classes (intersections, unions or complements), property restrictions based on value constraints and cardinality constraints, and so on (Hendler & van Harmelen, 2008). As a result, it is possible to define restrictions in order to facilitate the conceptual reasoning.

The OWL language was first subdivided into three main categories of sublanguages (or dialects) with different degrees of expressiveness designed for different uses: OWL Lite, OWL DL and OWL Full. OWL Lite provides the expressivity required to define classification hierarchies with simple constraints (e.g., cardinality constraints are limited to values 0 and 1). OWL DL, so called because of its correspondence with description logics, combines greater expressiveness with the capacity to retain computational completeness and decidability. This means that all conclusions are guaranteed to be computable and all computations will end in a finite time. These two features make it the most widely used language in the Knowledge Representation community since they are the basis for supporting automated reasoning. Finally, OWL Full provides greater expressiveness but without computational guarantees. It can also be described as an extension of RDFS by adding semantics with the additional OWL features where all constructs can be used in any combination (Allemang & Hendler, 2011).

A new version of OWL, OWL 2[68], was developed in 2009 providing new improvements such as syntactic sugar to make some common statements more user-friendly, simple metamodelling capabilities, and an extended support for datatypes, annotation capabilities and expressivity through three different profiles: OWL 2 EL, OWL 2 QL and OWL 2 RL. These three profiles all provide a limited subset of the expressiveness that is provided by OWL 2 DL (Golbreich, Wallace, & Patel-Schneider, 2012). The relation between the syntactic subsets (profiles) of OWL 2 is shown in Figure 3.3. More details about OWL 2 profiles can be found in Motik et al. (2009).

[68] OWL 2. Retrieved from https://www.w3.org/TR/owl2-overview/.

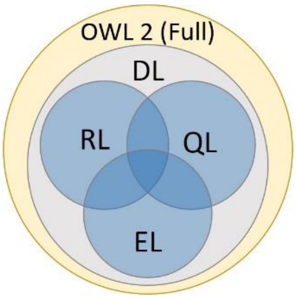

Figure 3.3: Venn diagram showing the relation between the OWL 2 profiles (sub-languages) (W3C, 2009).

There are other languages that are built upon RDF and RDFS to provide different kinds of standardized meaning for different purposes. Most vocabularies based on these languages are designed to be used for the description of conceptual schemes in order to provide greater standardization of them and facilitate interoperability. For example, SKOS (Simple Knowledge Organization System)[69] provides a vocabulary for the representation of the basic structure and content of concept schemas such as thesauri, classification schemas, taxonomies and other similar controlled vocabularies (see Section 3.1.3). Another example is Umbel (Upper Mapping and Binding Exchange Layer)[70], a lightweight ontology designed to facilitate interoperability with external datasets and domains.

There is also a large number of ontologies that have been designed to create vocabularies that unify worldviews across domains. This way, domain ontologies can be found, for example, to describe geographical content (e.g., GeoNames ontology[71]) and the roles and relations between people (e.g., FOAF[72]). In creating these ontologies, languages like Umbel provide a scaffolding to facilitate the linkage and interoperability between them. The features provided by these languages are enabling the publication of a large number of datasets[73] on the Web described according to these ontologies. There are multiple benefits in doing this, for example the possibility of linking data between different data sets. Search engines can use these connections between the data, for example, for discovering and finding information in a way that was not possible before.

Some domain ontologies have also been designed to be applied directly or indirectly in the AEC industry. An example is GoodRelations[74], a lightweight ontology designed for

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[69] SKOS. Retrieved from http://skos.um.es/TR/skos-primer/.
[70] UMBEL. Retrieved from http://www.umbel.org/.
[71] GeoNames is an ontology to describe the features of GeoNames, a geographical database accessible on the Web, where the feature classes and codes are described using the SKOS language (Vatant & Wick., 2012). Retrieved from www.geonames.org/ontology/.
[72] FOAF (Friend of a Friend) is an RDF vocabulary for expressing metadata about people developed by Brickley and Miller (2000). Retrieved from http://xmlns.com/foaf/spec/20070524.html.
[73] A "dataset" is "*a set of RDF triples that are published, maintained or aggregated by a single provider*" (Alexander, K., Cyganiak, R., Hausenblas, M., & Zhao, 2011), https://www.w3.org/TR/void/.
[74] GoodRelations ontology (Hepp, 2011). Retrieved from http://www.heppnetz.de/ontologies/goodrelations/v1.html.

exchanging information about products, offers, points of sale, prices, and terms and conditions on the Web. Its possible application for this sector has been investigated in different research projects relying on Linked Data principles. One of the examples is BauDataWeb, a data repository of building and construction materials domain for the Austrian industry implemented using this ontology. The technical approach, results and experiences gained in BauDataWeb were presented by Radinger, Rodriguez-Castro, Stolz, and Hepp (2013). Another example is the ISES[75] project, where this ontology was applied to develop a smart catalogue of building products, and associated services, for prefabricated building elements (Semenov & Tarlapan, 2014). The approach adopted and results achieved in this project are discussed in Chapter 4 of this document (see Section 4.2.4). However, the use of the GoodRelations ontology has different drawbacks to describe information about product data, for example in aspects such as the difficulty to represent the large number of properties that can be required in the building life cycle and versioning (Gudnason & Pauwels, 2016). Gudnason and Pauwels (2016) conclude that the elaboration of an ontology to represent the information about building products remains an unresolved issue.

The specification of the data described using Semantic Web Languages would be meaningless if there were no language for querying them. This language is SPARQL (SPARQL Protocol and RDF Query Language), a standard query language based on SQL designed to query information defined in RDF and RDFS. Among its characteristics, it includes a protocol layer on top of HTTP allowing third-party Web clients to query RDF data remotely, for example to extract an entire RDF sub-graph. One of the advantages of SPARQL compared with SQL language is that it is based on the RDF Turtle serialization. This way, non-expert users of databases may be able to perform queries easily through graph pattern-matching clauses.

All these Semantic Web languages (RDF, RDFS, OWL and SPARQL) can be combined and applied according to different uses and needs. In the AEC industry, they can be applied basically for two purposes: (1) to support interoperability between BIM applications and systems, and (2) to facilitate reuse and data integration to improve the management of BIM in different aspects.

Some of the research conducted during the past two decades has aimed to solve interoperability problems using methods and techniques from the field of ontology engineering. For example, Seo et al. (2005) proposed an ontology-based method for integration of semantic data. In their approach, ontologies are used as a formal method for representing the feature definition of different modelling CAD systems, using the STEP specification as an upper ontology. Through a bridge system, links are provided between ontologies of CAD systems and the shared ontology. This way, the bridge is

[75] ISES (Intelligent Services For Energy-Efficient Design and Life Cycle Simulation) is a research project, funded by the 7th Framework Programme, whose aim is to "develop ICT building blocks to integrate, complement and empower existing tools for design and operation management (FM) to a Virtual Energy Lab". Retrieved from http://ises.eu-project.info/.

provided by creating mappings between two features that are defined differently in two CAD systems but which represent the same meaning. Another example for addressing interoperability was proposed by Abdul-Ghafour, Ghodous, Shariat, and Perna (2008). In this case, the authors developed an ontology for sharing CAD models built in OWL DL language and using the SWRL (Semantic Web Rule Language) for enriching the expressivity. As a result of the popularization of IFC as a standard for building data exchange, many research efforts have focused on the development of ontologies based on (or compatible with) this standard (see Section 3.2.6).

3.2.2. Linked data approach

Another part of the research conducted to address interoperability issues deals with the exploitation of the abilities of the Semantic Web technologies to create links between different data on the Web, a method referred to as the linked data approach (Berners-Lee, 2006; Bizer, Heath, & Berners-Lee, 2009). Currently, building projects developed using BIM methodology use tools and systems that operate in isolation from each other. This situation leads to a scenario where data are enclosed within silos, since they are represented according to various internal data structures. Therefore, when project stakeholders need to exchange information, they have to deal with the problem of having BIM models defined in different data structures and formats, stored in closed systems.

The application of linked data provides an alternative to deal with the physical and semantic interoperability problem. Using this approach, the data of building models developed throughout the building life cycle can be effectively connected (Böhms, Plokker, Charvier, Madrazo, & Sicilia, 2010; Pauwels, 2014). Data from BIM models can also be linked to related data sources (e.g., product catalogues, regulations, sensors, occupancy, climate and GIS). The value of accessing and reusing data resources available on the Web can be greater in this second context of linked data usage when they are provided as linked open data.

The emergence of Semantic Web technologies made the linked open data (LOD) initiative, driven by the W3C Consortium, possible. This initiative is the result of the combination of two concepts: *linked data (LD)* and *open data (OD)*. The first term, linked data, refers to the method used to connect data across dereferenceable URIs on the Web, namely it addresses how information can be connected (linked) on a data level. The second, open data, refers to the fact that the data are available to everyone through free access on the Web. Through the combination of these two concepts, the aim is to extend the domain of the Web by publishing different data sets with different types of information described in open standards such as RDF, and where the data are linked between them. In this way, by linking the data used to describe information as RDF graphs in documents provided on the Web, it is possible to create a network of linked data – an LOD cloud – accessible as a global database for any application (Cyganiak & Jentzsch, 2011).

The idea of an LOD cloud including linked data somehow related to the AEC/FM domain can be useful for different applications, particularly for the development of building projects. As stated in the previous section, one of the most immediate applications is to facilitate reuse and data integration. In the development of building projects, different information may be required during the design process (e.g., energy simulations, bill of materials, cost planning and other estimations). Part of this information is generated within the scope of the project. Nevertheless, other information needs to be consulted (e.g., topography, geography, cadastre, climate, regulations, certifications, urbanity and GIS) and added (e.g., information about building components and products, including parametric component models and the information required for their estimating and calculation), as necessary. Today, consulting all this information is a time-consuming task. Sometimes it is difficult to locate the corresponding documents and specifications, interpret them in an appropriate manner and apply their rules to the information of the project. As a result of these inefficiencies, the sector is looking for new solutions. A linked building and related data approach is presented here as an alternative. However, the feasibility of this approach requires information to be available, accessible and, most importantly, linkable at data level (Figure 3.4).

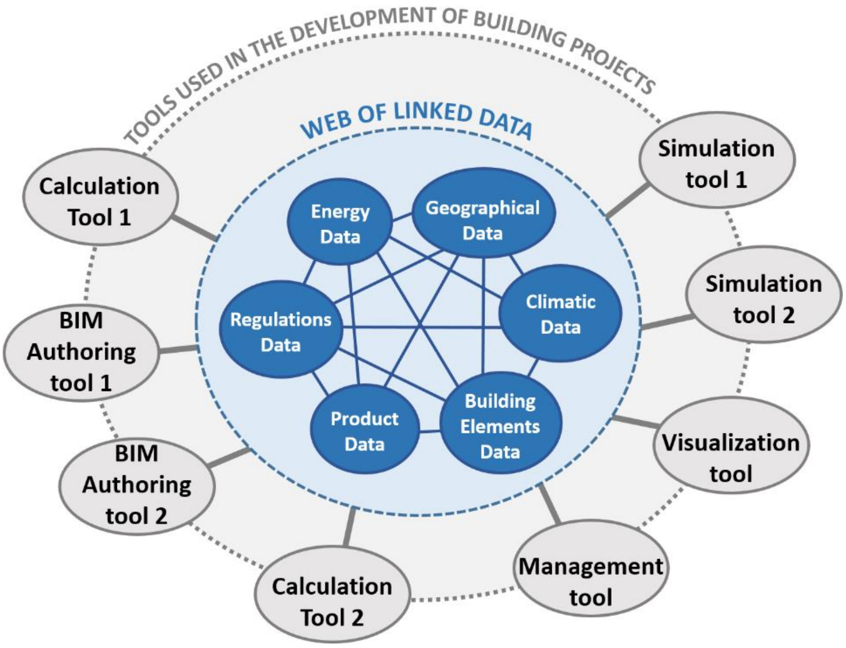


Figure 3.4: Linked data approach applied to provide data related to the AEC domain in the context of a Web of linked data, making them accessible to any application that needs to use them (Costa, Valderrama, & Jardí, 2016).

Through this linked data network of different AEC domains, different applications, services and plug-ins for design programs can be created, providing the capacity to interpret and reuse data automatically depending on the need. However, the success of this endeavor depends largely on the involvement of data providers, that is, governmental institutions, manufacturers, regulators, public administration and others. The problem is that most of them are still scarcely aware of its benefits, although an increase in the structured data sets published on the Web by the governments themselves has been observed (Cheptsov, 2011).

Returning to the interoperability problem between BIM applications, the linked data approach has been suggested in different research works as a strategy to address it. For example, in his Ph.D. thesis "*Reconsidering information system support for architectural* *design thinking*" (2012), Pieter Pauwels discusses the possible benefits of having the data structures of the information systems used in architecture, linked on a data level, as a means to improve the interoperability. An option that is investigated is the publication of the data by creating a network of linked data on the Web accessible to any application (Figure 3.5).

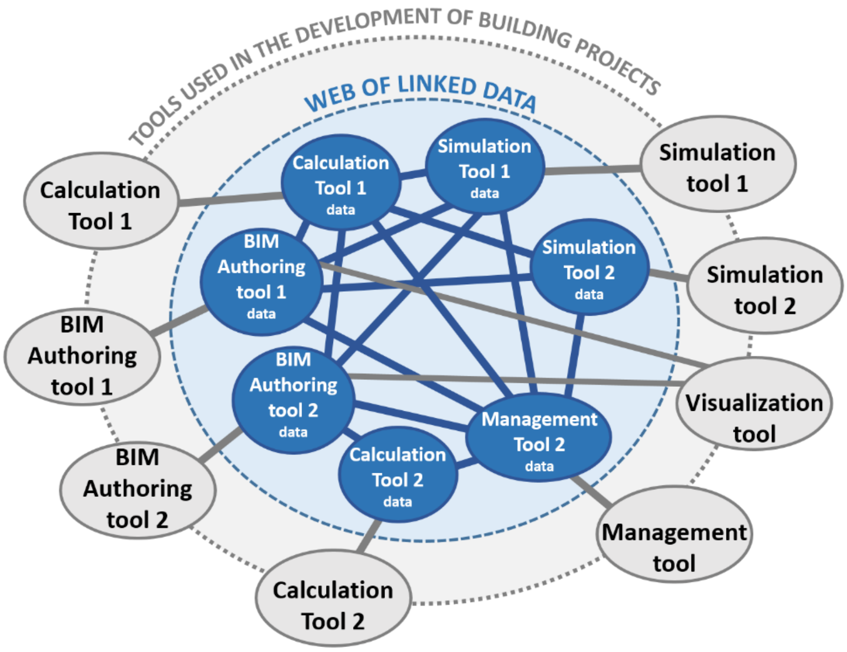


Figure 3.5: Linked Data approach applied to provide data of AEC software in the context of Web of linked data, making them accessible to any application that requires to use it (original source: Pauwels, 2012).

Today, an important part of the research aimed at solving interoperability problems in the AEC industry through the application of methods based on the linked data approach focuses on management and energy efficiency in buildings. The design and construction of a modern building involves a different range of information domains (maintenance, operation, financial, scheduling and others). Interoperability between information produced in these domains could help to provide a holistic management of the building, for example by identifying possible inefficiencies without altering the maintenance function of the building and the optimization of the energy consumption (O'Donnell, Corry, Hasan, Keane, & Curry, 2013). A number of methods have been proposed in recent years based on linked data to deal with this lack of interoperability. For example, Corry et al. (2013) proposed a data-driven approach to optimize building performance using a structured performance assessment framework where an ontology is created to describe the overall domain, including the required parts of the Metrics Ontology (Pedrinaci & Domingue, 2009) and the Semantic Sensor Network (SSN) ontology (Compton et al., 2012).

In the particular field of energy efficiency, Curry et al. (2013) proposed the use of linked data as an effective mechanism to provide interoperability between data sources from different domains in the development of cloud-based building data services. Other research work proposing similar approaches for the area of energy efficiency can be found in (Costa, Sicilia, Lilis, Rovas, & Izkara, 2016; Degeler et al., 2013; Kadolsky, Baumgärtel, & Scherer, 2014; Perez, Larrinaga, & Curry, 2013; and Sicilia, Costa, Corrado, & Gorrino, 2015).

3.2.3. Reasoning and rule languages

Among the most important features, Semantic Web languages provide the capacity for automated reasoning through machine-processable data representation formats. Automated reasoning can be required for different purposes, tasks and aims: for example, to verify whether an ontology is well formalized, to ensure its quality during the development or to infer new knowledge through simple queries, among other uses. The software used to carry out reasoning is called a *reasoner*, although it may also be called a reasoning engine, inference engine, rule engine or semantic reasoner. Formally, it can be defined as a piece of software that uses inference rule to infer logical consequences from a set of asserted facts (axioms). The efficiency with which the reasoning is carried out depends on the algorithms that are implemented and how they are applied.

Different levels of reasoning can be achieved depending on the expressivity of the Semantic Web languages. One of the requirements to apply reasoning is the decidability. This term refers to the condition that for any formula described through a language, there must be a method (algorithm) capable of deciding in a finite number of steps whether it is true or false. In order to guarantee the decidability, the problems of satisfiability, subsumption and instance retrieval need to be faced. This requirement motivated the design of the Semantic Web languages based on Description Logics (DL), for example OWL DL (Ian Horrocks & Voronkov, 2006), taking into account the potential of reasoning capabilities applied within the domain of these technologies.

DL-based languages provide formalisms capable of representing the traceability of reasoning, decidable fragments of First-Order Logic (FOL). The OWL DL and OWL 2 DL family languages include the specification of restrictions “to retaining computational completeness and decidability” (Deborah & Van McGuinness, 2004; Horrocks, Kutz, & Sattler, 2006; W3C OWL Working Group, 2012). However, ontology languages have been designed, in general, to address taxonomic reasoning problems, whereas reasoning problems involving data require additional rule-based systems (Farias, Roxin, & Nicolle, 2014). Defining the rules in a separate layer may be necessary to provide: more expressivity to customize rules; more dedicated language for rule-based systems; support for built-in operations (e.g., mathematical and string operations) (Horrocks et al., 2004; O’Connor, Shankar, Nyulas, Tu, & Das, 2008); descriptions of relations that cannot be provided by the OWL languages; and sharing and reuse of existing rules on the Web (Rattanasawad, Saikaew, Buranarach, & Supnithi, 2013). Some of the rule languages designed for the Semantic Web are *SWRL* (Ian Horrocks, Patel-Schneider, Bechhofer, & Tsarkov, 2005), *FOL-RuleML* (Boley et al., 2005) and *Jena* (The Apache Software Foundation, 2009).

Taking into account their purpose, rules created with these languages are also known as *inference rules*, although some authors (Esfahani, Fuchs, & Scherer, 2014; Weise, Liebich, Tulke, & Bonsma, 2009) refer to their use as a *rule-based linking approach*. They are defined as IF-THEN clauses containing logical functions and operations expressed in some rule language (Rattanasawad et al., 2013). This way, inference rules facilitate the extension of the information – which is defined in the IF-part of the rule – with data that can be logically inferred – defined in the THEN-part of the rule (Weise et al., 2009) – if the condition is satisfied. Inference rules can be applied in isolation, or as a group of interrelated inference rules, in order to "check" the data in an RDF graph by extracting the corresponding conclusions.

Rules are particularly important in the AEC industry, for example to comply with the boundaries, barriers, targets and other criteria that are part of the description of a building project. These can include different types of regulations (safety legislations, building codes, energy and acoustic performance, and urban plans, among other possible regulations imposed by governments) at various scales (municipal, regional, national and international) that need to be considered for the design, fabrication, construction and maintenance of a building. The implementation of BIM and the inclusion of the parameterization in the design facilitates the application of most of these rules through automated checking processes on the BIM.

The idea of using a logical basis in regulation compliance checking was proposed in different research works (Breaux, Vail, & Antón, 2006; Kerrigan & Law, 2003). For example, Cheng, Lau, Law, Pan, and Jones (2008) proposed a method to link the concepts of existing taxonomies to regulations in order to facilitate the retrieval of the associated legislative text. Within the context of BIM, different research works in the area of automated rule checking have been conducted by different authors[76]. For instance, Eastman et al. (2009) analysed the possible use of IFC as a neutral model to which the implementation of regulation compliance checking procedures could be standardized. To address this issue, they proposed to interpret rules in a machine-processable format "in a manner that the implementation can be validated as consistent with the written rule" (Eastman et al., 2009). The idea behind is to shift responsibility to translate a rule into a logic language (e.g., described as a predicate logic) outside of the programming of the tools. Among the implementation methods they proposed, a semantic rule-checking based on the predicate logic-based language fits well for a context of a BIM representation through Semantic Web languages. This technique was applied by Pauwels et al. (2011) for acoustic performance checking purposes, demonstrating the feasibility in the use of the logical basis of Semantic Web languages for semantic rule checking. This application case is discussed in more detail in Section 5.2.1.

3.2.4. Combining building information and rules

Two different approaches can be suggested to transform and prepare the information in a BIM model into a format (RDF graph) that can be combined with a number of formal inference rules:

[76]A review of the main strategies in the application of semantic rule-based checking systems in the AEC industry is provided by Pauwels and Zhang (2015).

1. **By developing ontologies for each BIM authoring tool.** Through providing ontologies representing the data structures of the different BIM modelling platforms, semantic representations of BIM models could be obtained according to each native format.
2. **By using a common standardized ontology to represent BIM data.** This approach focuses on the use of ontologies based on consolidated standards such as IFC. A part of the investigation of reasoning methods over BIM models is currently focused on the use of an ifcOWL ontology.

The analysis of the application of Semantic Web technologies in the AEC industry reveals that a significant effort has been placed on expanding the capabilities of existing interoperability standards. A review of the main methods and solutions proposed over the last years found in the literature review is provided below from two perspectives: building and product data.

Two decades of searching for different solutions based on the use of Semantic Web languages to provide transformations of the IFC schema into semantic model representations have resulted in the creation of different versions of IFC ontologies described in the Semantic Web languages. One of the first research works in this area was initiated by Katranuschkov, Gehre, and Scherer (2003). They created an ontological framework as part of an extensible and open architecture to access data in IFC format. The first attempts to apply Semantic Web technologies to improve the interoperability through IFC were provided by Schevers and Drogemuller (2006), who developed a prototype to support the search for a more appropriate mapping between entities and attributes from the IFC schema in EXPRESS and STEP part-21 to the corresponding classes and slots in OWL. Simultaneously, Beetz, Leeuwen, and de Vries (2005) derived an OWL notation from the EXPRESS schemas of IFC, which is one of the ones most used currently (Figure 3.6). In his Ph.D. thesis, Beetz (2009) discusses the trade-offs between the expressiveness, computational decidability, readability and compatibility of methods and algorithms to derive this notation.

EXPRESS construct	OWL construct
ENTITY	Class
SUB/SUPERTYPE	subClassOf
SELECT	Class and subClassOf
INVERSE	inverseOf / InverseFunction-alProperty
ENUM	DatatypeProperty […] owl:DataRange […] owl:one of […] rfd:List or enumerat-ed classes.
Cardinality constraints	owl:cardinality, owl:minCar-dinality, owl:maxCardinality
Simple Types	Simple XML Schema types
WHERE domain rules	Possibly through SWRL rules in future
collections: LIST, SET, BAG, ARRAY	Only unordered (?)

Figure 3.6: An excerpt of mapping between IFC EXPRESS schema and OWL constructs (Beetz, Leeuwen, & Vries, 2005b).

The growing interest in methods and readily available implementations based on ontology-driven architectures and their potential applicability to provide semantic interoperability between information systems used in the AEC industry (Beetz et al., 2009), has led the buildingSMART consortium to consider the future development and maintenance of ifcOWL as one of their technologies. The ifcOWL provides “extensions towards other structured data sets that are made available through Semantic Web technologies” (BuildingSMART, 2015). The first official version of the ifcOWL ontology provided after its adoption by buildingSMART was developed by Terkaj and Pauwels (2015) using the OWL 2 DL ontology language. They developed a conversion procedure based on the IFC4 ADD1 EXPRESS version to enable conversion of IFC models (instances) into equivalent RDF graphs (Pauwels & Terkaj, 2016).

The application of Semantic Web technologies to extend the capabilities of the IFC have been investigated and implemented in various research works and projects: HESMOS (Guruz, Katranuschkov, Scherer, & Geissler, 2014), ISES (ISES, 2014), Proficient (Bonsma, Bonsma, Zayakova, & Böhms, 2014), DURAARK (Edvardsen et al., 2016) and STREAMER (Iadanza et al., 2015), among many others, funded under European Commission programmes for research and innovation. Most of these research projects have been aimed at providing semantic interoperability between information systems used in the AEC industry, while others have addressed semantic rule-checking processes for reasoning purposes, conversion of IFC information and data integration.

Methods to facilitate the exchange of data through the use of standards have also been adopted from the perspective of product data, in the AEC industry and also in others fields such as manufacturing. Standards for product data inoperability have been designed to provide a computer-interpretable representation of this information and to enable exchange between industrial production information systems. One of the most widely used standards in many industries is ISO 10303 – more commonly known as STEP (STandard for the Exchange of Product model data). This standard is presented as an alternative to proprietary formats by providing a standardized way to represent and exchange product information throughout the product life cycle (PLC). Data schemes in STEP are described in the EXPRESS modelling language (ISO 10303-11:2004, 2004), a part of the STEP standard of which the first version was released in 1994. Information can be represented according to EXPRESS schemes in different ways. One of the most commonly used forms is through the STEP-File format (ISO 10303-21:2016, 2016), another part of the STEP standard of which the first version was also released in 1994. One advantage of STEP is the ability to formally validate the data with the corresponding schema.

Although STEP is presented as a successful standard to exchange information of products, it has limitations regarding semantic interoperability. Patil, Dutta, and Sriram (2005) outlined two of these limitations as follows. The first is related to the restrictions that limit the scope of schemas used to exchange the information between CAD applications. Since these schemas need to be shared among different CAD tools, resulting schemas are limited to the common information subsets among them. The second limitation is directly related to the translations of semantics. In this case, they argued that STEP only enables to translate terminologies between different CAD systems. As a result, part of the meaning, for example the meaning associated with the design intent, is lost during the exchange (Patil et al., 2005). As an alternative to these limitations, they proposed an ontology-based framework to enable this exchange across different application domains. While information about products is described using a created language called “Product Semantics Representation Language” (PSRL), a semi-automatic procedure is used to determine mappings between equivalent concepts in the vocabulary of applications. To achieve this aim, they suggest the requirements for this semantic interoperability are focused on the translation of terminologies. This way, through a product ontology described in PSRL, the meaning of product information can be captured. The outcome is a foundation of minimum common requirements necessary to represent product data rather than creating a new data model such as STEP. The most critical part is when performing the mapping between two ontologies. This is achieved through logical reasoning by comparing all terms’ definitions from both ontologies. The problem here is the need for a table to represent the semantic equivalence between terms, which requires the specification of mappings one by one for each new CAD program.

In a further step, and to improve semantic interoperability, Matsokis and Kiritsis (2010) developed a single ontology based on OWL-DL (Web Ontology Language – Description Logics), providing better capacities for reasoning. Following a similar approach, Chaparala, Hartman, and Springer (2013) proposed a data translation methodology based on the creation of a neutral core product ontology to facilitate the exchange of product information between CAD systems including its semantics. Through the combination of this ontology with STEP, they stated that it is possible to exchange any product data from multiple CAD applications. The process starts with the export of a product model in STEP file format from an initial CAD system. Then this file is loaded into an ontology editor such as Protégé. Through the “OntoSTEP” middleware, a plug-in for Protégé created by the National Institute of Standards and Technology (NIST), EXPRESS schemas are extracted from STEP-files and converted into OWL-DL versions. To facilitate the translation back to STEP files to be imported into CAD systems, they developed a plug-in to provide this conversion by using the OWL-API, an open-source Java API developed by the University of Manchester. However, the results with the application of this method revealed several inconsistencies. For example, some entities and attributes are missing after the translation process. Another limitation lies in the different ways in which STEP is implemented in CAD systems.

Within the AEC industry, methods and systems based on the application of the Semantic Web technologies have also been proposed to facilitate the exchange of product data from catalogues compatibles with the IFC standard. For example, Shayeganfar, Mahdavi, Suter, and Anjomshoaa (2008) created a version of the international framework for dictionaries (IFD) model implemented using the Semantic Web technologies. Specifically, information about Skylights components is represented as RDF data. However, inferences were limited to a convenient formulation of queries to access a single database. To overcome these limitations, Beetz and Vries (2009) proposed an extension of this method for heterogeneous data sources distributed over different locations, also using Semantic Web technologies. First, they created a lightweight ontology consisting of concepts and instances based on the IFC standard, tested for precast concrete products. The ontology was developed as the main part of a four-layer framework implemented as a prototype. After its creation, they serialized the ontology as a set of RDFa statements in order to facilitate the scraping of the information by Internet agents. The authors claimed that their solution could be an alternative to the buildingSMART Data Dictionary standard, as this is too wide and leaves too much scope for interpretation of how to structure and use concepts and their instances. They also argued that an architecture that integrates interfaces based on SOAP APIs and SPARQL endpoints is more capable of providing complex searches in a direct way than other implementations based on STEP/SOAP. Finally, Beetz and Vries suggested that greater support for the application of inference rules must be provided, as well as a more optimal balance between generality and expressiveness, as these need to be considered to improve the current performance.

Methods based on the application of Semantic Web technologies have also been proposed to exchange data across multiple sources. These methods are presented and discussed in the next section.

3.3. Data integration

The need to connect different data sources to produce an integrated information system, or a shared database, has been investigated for years as a way to exploit data in multiple domains and for different applications (e.g., data mining and decision-making). Here, the term "data integration" refers to the process used to carry out this integration, which can be performed in an automated or semi-automated way using various methods and technologies. In this section, we look at data integration based in using ontology engineering and Semantic Web technologies to improve and automate the data exchange between information systems. The role of ontologies and concepts related to ontology mediation are reviewed and the methods proposed for their application are documented. Finally, we examine the extent to which these methods are being applied in the AEC industry and whether they are actually facilitating interoperability.

In many industries, the automated integration of multiple heterogeneous data sources is becoming necessary to respond more efficiently to the business needs: to increase quality, to improve decision making and planning processes, to extend the scope of the analyses, and so on. In the case of the AEC industry, data integration can serve several purposes. One of them is to provide interoperability in data exchange using multiple sources. In the development of building projects, information from different sources may be necessary, for example, to carry out performance analyses of the building at the design stage. A clear example can be found in building energy simulations that require information about their design along with data about occupancy and climate profiles.

Data integration may also be necessary at the building operation and maintenance stage. The growing concern to reduce carbon emissions – reflected in the policies issued by the governments in many countries – and the need for energy cost savings, for example, are driving building owners to require new decision support systems to reduce the energy consumption of their buildings. These systems are increasingly requiring information from more various data sources (e.g., climate, occupancy and social patterns) and from building sensors (e.g., light, temperature and humidity) in order to provide more accurate results. The need to combine, organize and present all this information to the users (mainly, building owners and building energy managers) in a timely and easy-to-understand manner requires a common layer to assure interoperability between data sources. A flexible way to facilitate this interoperability can be through data integration methods based on Semantic Web technologies.

Data integration may also be required for the data generated outside the context of building projects but that are required for their development. Data about building site, cadastre, regulations, building products and materials, certifications or urbanity, among others, are typically manually consulted, accessed and entered in the AEC software by architects, engineers and others specialists. However, it is often difficult to make efficient use of these data in projects since they are usually found scattered and distributed in different sources, formats and systems. The integration of these data along with a BIM model can provide greater automation in their reuse into the processes developed within these domains.

3.3.1. The role of ontologies

Typically, techniques for data integration have focused on providing more efficient methods to cope with the high costs resulting from the lack of support in defining this integration in an automated way, leading experts and engineers to take a long time to define a semantically correct integration (Bussler, 2003, as cited in Bouras, Gouvas, & Mentzas, 2008). Solutions to address conflicts that arise from the heterogeneity of data involve dealing with interoperability at different levels: *system*, *syntax*, *structure* and *semantic* (Sheth, 1999). Among them, semantic heterogeneity conflicts are the most difficult to solve. These conflicts mainly arise when defining the correspondences between the terms included in different data sources with the same or similar meanings, which must be addressed both at schema level and instance level. Semantic-based solutions to help deal with semantic heterogeneity conflicts are known as *ontology-based data integration*.

During the last two decades, several authors have researched the use of ontologies to integrate heterogeneous data sources. For example, Uschold (2000) proposed using a global scheme (global ontology) as a mediator between the different schemes (local ontologies) corresponding to the data sources to integrate. In this work, the term "local ontology" refers to ontologies that needs to be created to represent the information of each data source, independently of the others, while the term "global ontology" refers to the ontology that need to be created to provide the unified view of the data. Based on this approach, Wache et al. (2001) proposed three alternatives to achieve data integration: *single ontology approach, multiple ontology approach* and *hybrid ontology approach*. Using the single ontology approach, a single ontology is created to provide a shared vocabulary to specify the semantics of the data. Using the multiple ontology approach, local ontologies are created for each data source, although it cannot be guaranteed that they share the same vocabulary. As a result of the use of inter-ontological mapping formalisms is required to overcome this deficit. In the hybrid ontology approach, local ontologies are created based on a global shared vocabulary that includes the basic terms of the global domain.

Buccella, Cechich, and Brisaboa (2003), proposed a data integration method, based on this hybrid approach, consisting of three stages: (1) building a shared vocabulary, which entails the analysis of information sources and search of terms (or primitives), and defines the global ontology, (2) building local ontologies, which entails the analysis of information sources and local ontology definitions, and (3) creating mappings between the concepts defined in the global ontology and the local ontologies using matching techniques. An aspect to be considered in the creation of global ontologies is that a language must be used for their specification in order to provide reasoning capabilities to satisfy the end-users' needs and purposes.

3.3.2. Ontology mediation

Ontologies can be an appropriate mechanism to deal with data integration challenges given their ability to explicitly specify the semantics of the terms. This way, different data sources describing particular knowledge can be reconciled when an ontological model that describes them can be obtained. In the field of ontologies, this reconciliation process is called *ontology mediation*, a structure-level matching that compares the structure of ontologies to find similarities.

However, ontology mediation requires addressing a number of issues in order to deal with semantic heterogeneity. Issues such as the specification of the overlaps and the mismatches between concepts, relations and instances in different ontologies are not easy to address. O'Brien and Cui (2000) classified these semantic heterogeneity issues, according to:

- **Semantically equivalent concepts:**
  (1) When different terms are used to refer to the same concept by two different ontologies as synonyms. However, from this assumption it cannot always be inferred that these concepts are semantically equivalent.
  (2) When concepts with the same meaning included in two different ontologies have different properties. For example, considering two ontologies that represent information about products, the concept product could include the property of colour in one ontology but not in the other.
  (3) When there are mismatches in the type of property. Following the example above, dimensions of products could be defined according to a set of measures. However, they could be provided in different measurement systems in each ontology (e.g., metric and imperial systems).

- **Semantically unrelated concepts:**
  (1) When two ontologies use the same name to define concepts with different meanings. For example, a concept known as "beam" may refer to a building structural component but also to a laser device.

- **Semantically related concepts:**
  (1) When a concept is defined with a more general meaning with respect to another. For example, products in one ontology can be classified according to

the concept "building components", whereas in another ontology they could be classified according to a more specific category, such as "prefabricated products".

(2) When the meaning of a concept can be represented in different ways. For example, a concept in one ontology can be represented by a set of concepts in another ontology.

(3) When the meaning of a concept is the same in different ontologies, but with nuances. For example, a "wall" element can refer to the external walls of a building but also the element that establishes the internal separation between the rooms of a flat.

(4) When there is a different conceptualization of the same thing. For example, one ontology can classify the concept of "building element" as a product whereas in another it can be classified as a building component.

There are different ontology-based approaches that can be applied to tackle the semantic heterogeneity problems described above depending on the conditions (e.g., the heterogeneity degree of the data sources) and context in which the integrated data will be used. These approaches can mainly be classified as: ontology mapping (based on the representation of correspondences between ontologies), ontology alignment (based on finding or discovering these correspondences) and ontology merging (based on the use of these correspondences to create new ontologies resulting from the union of them) (De Bruijn et al., 2006). Since mapping discovery to facilitate the ontology alignment – also referred as ontology matching – can become a difficult task to do manually, especially when it involves large ontologies, methods and algorithms have been proposed for its (semi)automation (Mitra, Noy, & Jaiswal, 2005).

3.3.3. Ontology matching

Ontology matching (or ontology alignment) refers to the process of establishing logical correspondences (mappings) between semantically related entities (concepts that have the same meaning) that are included in two or more ontologies. This process can be performed manually, semi-automatically and automatically. The first method involves a lot of handwork and poses reasonable doubts about achieving quality results. Conversely, fully automatic methods are far from being achieved in most of the application cases, for example if one takes into account issues such as having to deal with the semantic heterogeneity. Given this situation, most of the research focuses on semi-automatic methods.

As stated before, the most conflicting part in ontology matching is how to deal with the existing mismatches between ontologies. These mismatches are generally unavoidable since finding correspondences between two concepts included in various ontologies is very subjective and depends on how the reality is represented in each of them. For example, the concept "building product" in an ontology may have the same meaning as "building component" in another, or may not. This type of decisions will be subject to the interpretation of the alignment required to meet the needs of the application domain.

Similarities and mismatches between the terms contained in multiple ontologies have been investigated in various ways. Klein (2001) has identified two levels of mismatches:

(1) the language (or meta-model) level, where mismatches (according to the syntax, logical representation, semantics of primitives and in the expressivity of languages) occur when ontologies described in different languages are combined, and (2) the ontology (or model) level, where mismatches occur because of the combination of partly overlapping domains between two or more ontologies. Noy (2004) identified three dimensions for ontology matching: (1) mapping discovery as a process that involves finding similarities between two ontologies and determine what concepts and properties represent similar concepts, and so forth; (2) declarative formal representations of mappings, as a process that involves how to represent mappings between two ontologies to enable reasoning with mappings; and (3) reasoning with mappings (exploitation), as a process that involves choosing the type of reasoning according to the mappings done and the type of information to be obtained. Matching methods can also be distinguished according to ontology mapping techniques based on using the same natural language (monolingual ontology mapping) or different natural languages (cross-lingual ontology mapping) as discussed in Euzenat and Shvaiko (2007).

A number of tools and matching systems (e.g., Edna, AML, AOTL, LogMap, LogMapLite, MaasMtch, OMReasoner, RSDLWB, XMap2) have been designed to exploit alignments and matching operations between ontologies. According to Shvaiko and Euzenat (2013), software related to ontology matching can be divided into: (1) infrastructure middleware and (2) support environments to provide alignments for different purposes and scenarios (edition, processing, sharing and discussing, and model management). Independently of the case, ontology matching techniques are more critical for runtime applications, while when these are performed during the design, matcher selection and self-configuration are the most critical to ensure the appropriate quality and precision required in its application (Shvaiko & Euzenat, 2013). The quality of data linking is usually determined by two main measures (or indicators): (1) precision in the percentage of correct mappings and (2) recall in the percentage of correct mappings identified by the tool. Other typical metrics such as *Maximum F-Measure* (Jansche, 2005) combines recall and precision achieved with the optimal settings of an algorithm.

3.3.4. Current methods for data integration

Data integration methods implemented using Semantic Web technologies can be classified into two main groups: (1) based on data warehouse (Inmon, 1992; Kimball, 1996) and (2) based on mediators (Wiederhold, 1992). The first group of methods is based on data translation, where the data of the different sources are integrated into a common data repository – a data warehouse – following a transformation process. The disadvantage in this case is that the implementation is limited in terms of data storage and maintenance. The methods of the second group are based on query translation performed through a mediator system, which acts as middleware. Therefore, mediators – also referred as mediator-wrapper systems – do not contain data physically, but one may query them as if they had these data stored (Ullman, 1997). However, the limitation of mediators systems is that they depend on the connection with the data sources. As a result, if these are no longer available or if the data structure is modified, mediator systems need to be updated to reflect these changes. Techniques for implementing mediators have been proposed and developed over the years by different authors (Fiorelli, Pazienza, & Stellato, 2014; Karnstedt, Sattler, Geist, & Höpfner, 2003; Lassoued, Wright, Bermudez, & Boucelma, 2008; and others).

There are various scenarios in which a data integration process can be necessary. In some cases, data providers and developers of applications that integrate them do not maintain a direct relation in the process. For example, a data provider (e.g., product manufacturer) may be interested in that their data (e.g., information about the features of their products) can be reused and exploited for different purposes, but without knowing which these are. Most of the time, data providers have their data stored in relational databases, so they have to transform them into RDF format if they want to facilitate their reuse. This transformation requires a relational-to-ontology mapping process.

Strategies to expose data from relational databases as RDF data on the Web, without considering their representation in any specific domain ontology, are referred as direct mapping. It takes the data and schema of relational databases as input and generates an RDF graph (Arenas, Bertails, Prud'hommeaux, & Sequeda, 2011). Direct mapping is also referred in the literature as a means to materialize RDF graphs from relational databases. Although direct mapping is not directly related to data integration, various systems use this technique as a first step for data integration. An example is BootOX (Bootstrapper of Oxford) (Jiménez-Ruiz et al., 2015), a system that facilitates the automatic extraction of mappings from relational databases to OWL 2. Later, the system enables to import domain ontologies which can be aligned with the ontology automatically generated from one or more relational databases, or mapped directly to them (Jiménez-Ruiz et al., 2015).

Techniques to provide an automated extraction of mappings according to specific ontology domains have been investigated over the past two decades. For example, An, Borgida and Mylopoulos (2005) proposed a tool that enables inferring mapping formulas from the correspondences between tables columns of database schemas and data-type properties of classes in an ontology. To this aim, they apply semi-automatic transformations from a set of rules to generate ontological models from relational database models. These transformation rules allow equivalences to be established between basic formalisms where elements of a relational model such as tables, attributes (columns), relationships between primary and foreign keys, constraints and instances are transformed to classes, data-type properties, object properties, axioms and individuals, respectively. A column is normally mapped to a data-type property where cardinality can be specified unless it is a foreign key. In this latter case, a foreign key column can be represented or mapped in four different ways in ontologies: (1) as an object property (the most frequent), (2) as an inheritance class, (3) as a symmetric property, and finally (4) as a transitive property. Moreover, the transformation of a unique attribute (e.g., column ID) is represented by an inverse functional property (in OWL, there is owl:InverseFunctionalProperty) while primary keys are represented as an inverse functional property with a minimum cardinality of one.

Although there is a direct relationship between the basic components of a database schema and an ontological model, its transformation is subject to different known problems. Several authors have listed these problems. For example, Astrova, Korda, and Kalja (2007) enumerate the following:

- Loss of data: the result of the transformation should adequately describe the original data.
- Loss of semantics: not all constructs in a relational database can be mapped to an ontology.
- Focus on structures: besides the mapping of schema, mapping of data instances should be provided.
- Focus on data: data should be mapped with data-type descriptions.
- Applicability: in some cases, the transformation does not really generally limiting its scope.
- Correctness: the transformation should have provable correctness.

In order to address these kinds of problems and to support the data transformation and integration processes, the scientific community has taken an active role in the development of various database-to-ontology mapping tools, declarative languages to define the mappings from relational databases schemes to ontologies, and frameworks and services that use these mapping languages to transform the data from relational databases to RDF data. An example service is D2R Server (Bizer & Seaborne, 2004), a framework that facilitates the automated extraction of mappings and the publication of contents of relational databases into RDF format. In this platform, the mappings are specified in the D2RQ mapping language. R2O mapping language and ODEMapster processor (Barrasa-Rodríguez & Gómez-Pérez, 2006) make an integrated framework for the formal specification, evaluation, verification and exploitation of the semantic mappings between ontologies and relational databases. DB2OWL (Ghawi & Cullot, 2007) is another tool designed to automatically generate ontologies from database schemas, also using the R2O mapping language.

An example tool designed to facilitate the matching between database schemas and ontologies is COMA/COMA++ (Aumueller, Do, Massmann, & Rahm, 2005), where the ontologies can be specified in SQL, OWL and XML languages. In a similar way, RDOTE (Vavliakis, Grollios, & Mitkas, 2010) enable to instantiate an ontology with real data from relational databases. Other tools have been developed as plug-ins for ontology editors. An example is RDB2ONT (Trinh, Barker, & Alhajj, 2006), a plug-in for the Protégé ontology editor, although it no longer seems to be available in the latest versions.

More recent tools and frameworks to transporting data residing in relational databases into the Semantic Web use the R2RML language (Das, Sundara, & Cyganiak, 2012) to specify the mappings. Unlike the D2RQ language, R2RML is currently a W3C recommendation. Examples of these tools are MIRROR (de Medeiros, Priyatna, & Corcho, 2015) and AutoMap4OBDA (Sicilia & Nemirovski, 2016). The latter overcomes some of the limitations in the automated generation of the mappings by taking into account the attribute values of the data instances and the features of ontologies.

When dealing with data integration scenarios, ontology engineers responsible for extracting the mappings may choose to use some of the above tools. To determine which is the most convenient, some benchmarking tools have been created with the ability to evaluate the quality of the mappings provided by mapping generation systems. An example is the RODI[77] benchmarking suite (Pinkel et al., 2015). This tool (freely available) allows users to evaluate under the same conditions the quality of the mapping generated by these tools by providing a set of representative tests that include some mapping challenges.

Another application for ontology-based data integration to obtain data integrated through a target ontology is when the sources are already provided in RDF format, for example in files or RDF triple stores. Various mapping languages and engines have been proposed and implemented to enable the transformation of RDF data from one ontology domain to another. An example is R2R framework (Bizer & Schultz, 2010), which implements a mapping composition method capable to generate executable transformations. These can be defined through a language that enables to specify direct mappings between the concepts, but also their composition into a mapping chain (Bizer & Schultz, 2010). The reason for the development of this framework was that the last specification of SPARQL (1.0) did not provide mechanisms to transform data in these terms. However, a few months later a new specification (1.1) (Harris & Eaborne, 2010) was published including the CONSTRUCT query form to enable this type of transformations. Because SPARQL was the standard language for querying RDF data supported by the W3C, the R2R framework was discontinued.

The SPARQL CONSTRUCT query form enables to generate RDF graphs. While the CONSTRUCT clause enables to specify the graph pattern to be generated as a result of the transformation, constructed by replacing the values of the variables, the WHERE clause enables to specify the corresponding source pattern (Listing 3.1).

```
PREFIX foaf: <http://xmlns.com/foaf/0.1/>
PREFIX ex: <http://www.example.org/>

CONSTRUCT {
       ?x foaf:name ?name .
       ?x foaf:mbox ?email .
}
WHERE {
       ?x ex:hasName ?name .
       ?x ex:hasEmail ?email .
}
```

Listing 3.1: Simple example of a SPARQL CONSTRUCT query.

3.3.5. Application examples

Most examples where Semantic Web technologies have been applied for data integration purposes in the AEC industry have been developed within the academic research field. As introduced at the beginning of this chapter, one of the areas that currently seems to accumulate a greater interest in data integration is energy efficiency, both in the design and operation of buildings. The policies carried out in recent years to stimulate solutions

[77] RODI. Retrieved from http://www.cs.ox.ac.uk/isg/tools/RODI/.

for more efficient management of buildings, such as those being promoted by the European Union to reduce energy footprint and CO_2 emissions, have led to the investigation of data integration methods in different research works and projects.

An example is the Web-based Decision Support System (DSS) developed in the context of the OPTIMUS[78] research project (2013-2016). The system was designed to support the decision-making to optimize the energy efficiency of buildings. One of the main components of the system is a semantic framework devised to facilitate the required interoperability between the DSS and five different data sources: weather forecasting, decentralized sensor-based systems, social media, energy prices and renewable energy production. By means of Semantic Web technologies, information from these data sources is integrated according to an ontology: the OPTIMUS ontology. This ontology was designed to capture the information from the data sources that is needed to perform the prediction of the building performance. This was created by reusing two existing ontologies: (1) Semantic Sensor Network (SSN)[79] and (2) SEMANCO[80] ontology were reused (Figure 3.7). The results of this project show that ontologies are an effective way to integrate data from heterogeneous sources.

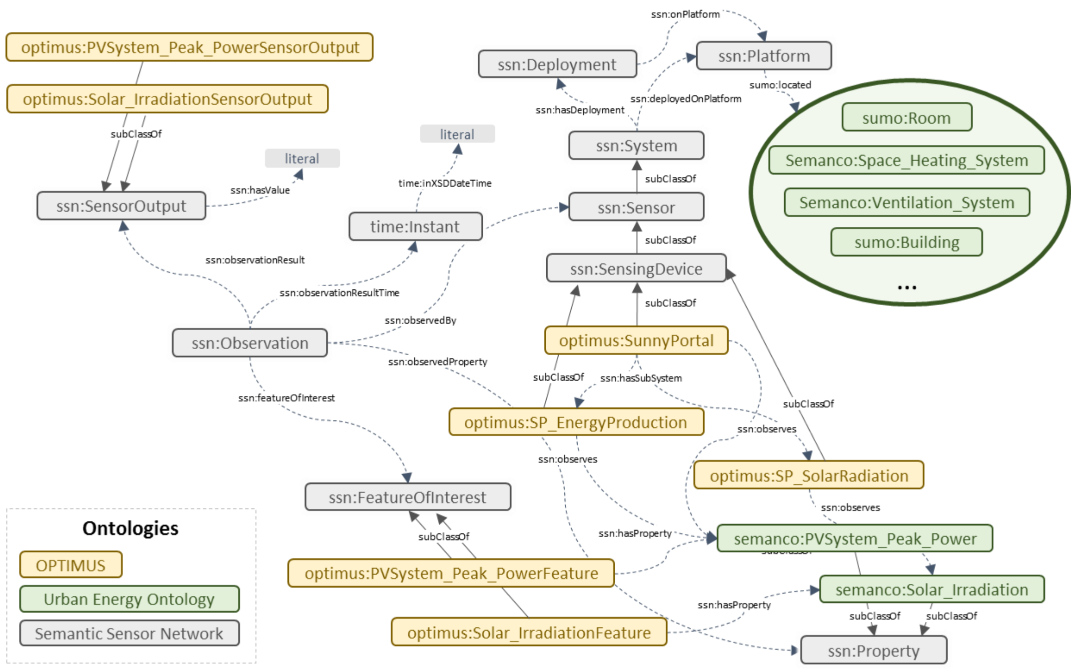


Figure 3.7: Extract from the OPTIMUS ontology (Sicilia et al., 2015).

[78] OPTIMUS "OPTIMising the energy USe in cities with smart decision support systems". Retrieved from http://optimus-smartcity.eu/.
[79] Semantic Sensor Network (SSN) ontology. Retrieved from https://www.w3.org/2005/Incubator/ssn/ssnx/ssn.
[80] SEMANCO ontology. Retrieved from http://www.semanco-project.eu/ontology.htm.

The use of ontologies in the AEC industry can also provide ways to integrate information defined at different scales, for example, at the building and urban scale. Currently, the most common open standards for representing these two types of information are IFC and CityGML, respectively. The need for solutions to integrate information about GIS and BIM, and their benefits, has been discussed in a large number of articles. In the last decade, several authors have proposed different methods to carry out the integration of data about these two models into a unified model. For example, de Laat and van Berlo (2011) proposed a method based on an extension of the CityGML, called GeoBIM, where part of the semantics defined in the IFC is translated to the GIS domain. As a result, part of a BIM model defined in IFC can be transformed to CityGML. The authors concluded that while it is technically possible to add semantic information of the IFC standard in the CityGML, it is difficult to add full IFC semantics. Moreover, they also state that solutions based on extending the CityGML schema only work in one direction.

Various methods based on the use of Semantic Web technologies have been proposed to in an attempt to overcome the limitations on combining information from both standards (CityGML and IFC) through shared semantics. For example, Karan, Irizarry, and Haymaker (2015) have confronted the semantic interoperability between BIM authoring tools and geospatial analysis tools. To this end, they created a BIM ontology in the EXPRESS language schema capable of encompassing all IFC classes with various attributes. In a second step, ontology mapping techniques have been applied to link concepts and relations with similar meaning from both ontology domains (BIM and GIS). This process results in the creation of a new ontology containing information from both domains. Finally, the information described according to this new ontology has been translated into Semantic Web standards to facilitate its querying through SPARQL queries.

Data integration can also be applied to the integration of building product data. The need to facilitate the integration of product data into the BIM systems is becoming an area of interest, not only to improve the efficiency of the processes carried out by the BIM users for the design of the building, but also to fulfil information needs that may arise during the remaining phases of the building life cycle. As already stated in previous sections, there is a need to facilitate a bridge between those who generate information related to the components and building products, and agents (public administration, manufacturers and generic online catalogues, among others) that could make use of this information at each stage, mostly during the design stage. Therefore, to provide this bridge, the information must be organized not only for easy understanding by the users, but also to enable programs and services to access it. With this purpose, some research efforts have focused on developing ontologies to facilitate the interoperability between content generators and designers, or end-users that make use (or reuse) of them, according to different specific domains. Another reason for their development is to facilitate methods to enable end users to find the products that meet the project requirements (Tah & Abanda, 2011). However, we have not found relevant work in the literature related to product data integration methods using these ontologies. The few references found are mainly based on ad hoc tools developed for very specific application cases.

3.4. Summary and conclusion

This chapter started with a review of the basic notions related to the knowledge representation and the fundamental concepts underlying the Semantic Web technologies and linked data. From the understanding of these concepts, different methods aimed at providing interoperability between information systems were introduced and discussed. In particular, methods based on data integration and their application were investigated to support interoperability in data exchange between information systems in the AEC industry. The feasibility of these methods to help overcome the current limitations in this exchange was examined by reviewing the literature and the results of research projects in which they have been applied.

Following this review, it was concluded that most of interoperability problems are due to the existing heterogeneity between data structures implemented in the software applications that are currently used in the AEC industry. In part, this is because applications are often tailored to the specific information needs of each discipline involved in the development of building projects. Each of the disciplines requires that information be represented and handled according to their specific needs (vocabulary, graphic representation, interface interactivity, etc.). As a result, project stakeholders have to deal with this heterogeneity when they need to exchange information. Interoperability problems occur at different levels: system, syntax, structure and semantics (Sheth, 1999). Technological solutions have been able to respond to the first three types (system, syntax and structure). However, solutions to address semantic heterogeneity in order to achieve semantic interoperability remain a challenge. As described in Chapter 2 (Section 2.3.1), semantic interoperability is essential to enable software agents to automatically (or semi-automatically) interpret information.

Interoperability standards have proven to be decisive in facilitating seamless data exchange in many industries. This is not the case for the AEC industry. As discussed in Chapter 2 (Section 2.4.1), standards such as IFC play a central role in providing a standardised semantic representation of building designs. However, it is difficult to provide a standard model compatible with all the existing data structures implemented in each BIM software. Likewise, it is difficult for software vendors to adjust the existing data structures of their models (of greater complexity) to IFC. Therefore, it can be concluded that interoperability problems will persist in the AEC sector, at least for the next few years.

From the review of the state-of-the-art methods to address the difficulties in providing interoperability in data exchange, it can be determined that Semantic Web technologies can be applied to support it, especially in data exchange scenarios that require the integration of data from different sources. This support is becoming increasingly necessary as there is a growing need to integrate BIM data with other data sources.

The increasing demand from AEC practitioners for more accurate results and alternative solutions is leading to the development of more sophisticated BIM software tools and systems, evolving from closed, stand-alone, and loosely coupled systems to networked information systems. As the capability of software applications to reuse and process information from different sources and domains increases, there is a greater need to improve their automatic interconnectivity to avoid the drawbacks of a manual entry of data by users. However, much of this information is currently not available online, so it has to be entered manually in the applications. This is intensive labour, prone to errors and therefore potentially inefficient. These problems do not only appear in the design and construction stages, but also in the facility management, when building owners and technical staff responsible for their operation and maintenance need a better understanding of the building's behaviour. Improving this understanding might require the integration of historical and monitoring data with data from external data sources (e.g., climate data from weather stations), as well as BIM data. Section 3.3.5 documented a research project in which Semantic Web technologies were applied to integrate cross-domain building data to assist building energy managers in optimizing energy savings.

Two cases can be distinguished where current software applications require information from various sources. In the first case, information from each source might be required separately and, therefore, users of these applications have to deal with interoperability to integrate all data sources. These types of exchange are often carried out with open or proprietary standards compatible between both tools. In the second case, the information from the different sources must be provided in a way that can be integrated into a single system, interoperability standard, file format, or data scheme. In this second scenario data integration methods based on Semantic Web technologies can provide support solutions for interoperability. Besides enabling automation or semi-automation of the data exchange process, the most important feature of these methods lies in their flexibility to adapt to new interoperability contexts, sometimes without having to modify the software. For example, new relations between the data can be defined through ontology editing tools. In Section 3.3.1, it was argued that ontologies have a central role to facilitate the integration of data. In ontology-based data integration methods, ontologies can be used to model the data sources and also to provide conceptualizations of target domains that effectively combine the data from the sources. Through the definition of mappings and data transformation rules between the ontologies, information of the data sources can be integrated to allow agents (human and machines) access through a unified view.

When applying this data integration approach to the AEC sector, information residing in different software applications can be automatically integrated to satisfy the needs of one or more target tools. An example can be found in the exchange of information to carry out building energy simulations. Currently, building energy performance (BEP) simulation tools require information from various data sources (building designs, occupancy, climate, etc.) which need to be accessible in an open file format. Retrieving all the information needed to perform the simulations is a cumbersome and labour intensive process which needs to be done by experts. Therefore, the automation or semi-automation of this process by implementing ontology-based data integration can overcome such limitations. An ontology that could be used in this case is the one that models the SimModel standard (O'Donnell et al., 2011; Pauwels, Corry, & O'Donnell, 2014), designed to represent the information of the domain of building energy performance simulations. In this way, through the use of this ontology it is possible to implement data integration solutions to improve the interoperability between BIM authoring tools and building energy simulation tools.

After examining the role of ontologies in data integration methods, it can be concluded that it will be easier for software developers to reuse ontologies for general use cases in data exchange. Of course, to be used in an efficient data exchange process, software tools should include these technologies as a part of their developments, in the same way most of them currently include importers and exporters based on the IFC standard. As established in the literature review, most efforts in developing ontologies to improve interoperability in the AEC industry are mainly focused on the IFC standard. In Section 3.2.5, the evolution of methods to develop ontologies from IFC schemas, such as those based on the conversion of EXPRESS schemas into ontology versions in OWL, named ifcOWL, has been traced. By using these ontologies, information contained in a BIM model and exported in IFC can be represented as RDF graphs. This way, data defined in an IFC model can be integrated with other building data. However, IFC models in RDF can be useful for reasoning processes, for example, by inferring useful information to support decision making (e.g., to assist in obtaining more optimal building designs).

An important benefit of data integration based on Semantic Web technologies lies in the availability and reuse of converters that enable the automation of the transformation of the data defined according to standards and information domains into RDF data. The use of these converters can help to create flexible solutions to address the interoperability in specific data exchange scenarios. Although these converters are useful to transform the data into RDF, the real difficulty lies in their integration. Here, the main obstacle appears in the extraction of mappings and transformation rules, a process that involves a collaborative work between ontology engineers and domain experts. In order to facilitate this extraction, matching techniques can be applied to facilitate the automatic discovery of semantic relations between ontologies. Some of these techniques were introduced in Section 3.3.3. It was also indicated that the most difficult issue in ontology matching is to solve mismatches between ontologies. For example, finding the correspondences between concepts with the same meaning in two ontologies is very subjective and depends on how the reality is represented in each of them. Dealing with these issues requires human intervention, not only to carry out the mappings between ontologies, but also to create transformation rules based on them, for example implemented through SPARQL queries using the CONSTRUCT form. This suggests that interoperability solutions through data integration methods for the AEC industry will continue to be developed in the next few years tailored to specific use cases in data exchange, and requiring the implication of ontology engineers working in collaboration with domain experts.

In this chapter, the application of data integration methods was also examined to integrate information which is not generated during the building project (e.g., product catalogues, repositories of BIM components, and building codes and regulations) but that is necessary for its development. In many cases, accessing, retrieving, and integrating this information into processes to carry out the development of BIM modelling becomes a time-consuming task. A clear example is the case of information related to the building components and products. The next chapter is mainly dedicated to the exploration of this case.

4

Building product information

In Chapter 2, the main inefficiencies in the use and exchange of data in the processes of exchanging information in the AEC sector were identified. They are mostly attributed to the difficulties to accessing information, the lack of adequate mechanisms for data retrieval and integration. The use of data integration methods based on Semantic Web technologies was postulated in Chapter 3 as a plausible solution to overcome these difficulties. In light of their potential, Chapter 4 describes how these technologies can be applied to integrate the data related to the domain of building components and products in order to facilitate their automatic processing on a semantic level. To address this question, the first part of this chapter examines the use of information about building components and products in BIM modelling, the role of manufacturers in providing it, and how product knowledge and expertise can be captured. A second part reviews the information and features about building products which are currently provided in BIM object catalogues and libraries operating over the Internet (e.g., formats, embedded information and plug-ins to connect to BIM authoring tools). A brief overview of the research conducted in recent decades on providing new strategies to facilitate greater interaction and reuse of BIM objects from catalogues is also offered. The third part of the chapter examines some methods based on Semantic Web technologies to provide data integration processes implemented in the research project BAUKOM.

4.1. Use in the BIM modelling

In this section we analyse how information about building components and products is used in BIM modelling, and the possible role that manufacturers can play in it. We start by examining the notions of industrialization and prefabrication in the BIM modelling process. These two concepts are examined from a historical perspective in the manufacturing industry.

4.1.1. Products in BIM processes

Each of the physical parts that make up a building (doors, windows, walls, slabs, etc.) can be defined by the term "building component"[81] or "building element"[82]. Building components or elements, and the way in which they fit together, should be systematically coordinated along the design and construction stages in BIM-based projects. In BIM, the building is represented through detailed three-dimensional models that describe how the building should be constructed. This description is defined as precisely as possible in order to avoid misinterpretations and errors during the construction tasks (Jørgensen & Skauge, 2008). The BIM model is based on a data structure where objects (conceptual entities) are represented by building components that can include various types of information and definitions: geometry, spatial relations, location, compatibility and connectivity with other elements, and aspects related to acoustic, thermal, structural, energetic, and other features. This information will be added progressively in the components of the BIM model over the different stages of building projects, and in general, in those of the building life cycle, according to the needs.

The decisions adopted in the design of a building depend on the information available at each stage of this process. In BIM-based projects, we need to consider the information required for the construction of the model. This information management can involve, for example, the choice of the methods to be used to acquire the information, the organization of the roles of project stakeholders, the workflows and so on. A key issue is the decision about the use of prefabricated components. There are some advantages in their use, depending on the type of project, with a different impact in the design and construction stages. For example, compared with components created *in situ*, prefabricated components can be replaced more easily when they become obsolete or broken, while in the construction stage, the advantage is that they can be produced at a lower cost.

The information required about building components and products in the BIM modelling depends on several factors such as the type of building (houses, schools, hospitals, hotels, etc.), type of project (private or public), the project delivery method chosen (DBB, DB, CMAR, IPD) (see Section 2.1.3), the size of the project and the roles of the participating agents. In this last case, architects, for example, can assume more than one role in small projects, while these same roles can be assumed by different specialized teams in large projects.

Typically, BIM-based projects start with preliminary versions of the design. These early models are made of generic components and materials that are easily found in the libraries

[81] The "McGraw-Hill Dictionary of Architecture and Construction" (Harris, 2005) defines the term 'building component' as "1. A building element which uses industrial products that are manufactured as independent units capable of being joined with other elements. 2. According to the NEC, any subsystem, subassembly, or other system designed for use in (or integral with) a structure or part of a structure, which can include electrical, fire protection, mechanical, plumbing, and structural systems and other systems affecting health and safety".

[82] The "McGraw-Hill Dictionary of Architecture and Construction" (Harris, 2005) defines the term "building element" as "an architectural component of a building, facility, or site".

of BIM authoring tools. However, although the use of information about real products is generally not required until more advanced design stages, some information about their features may be needed in the early stages of the design. This may be the case for energy simulations of buildings, the results of which may restrict the design alternatives. The optimization of the thermal conditions of a building implies the adequacy of the building products, requiring information such as the "heat transfer coefficient" value of the components. Figure 4.1 shows an example in which this information (framed in red) is included in a roof component, in this case provided on the BIM objects of the ISOVER manufacturer.

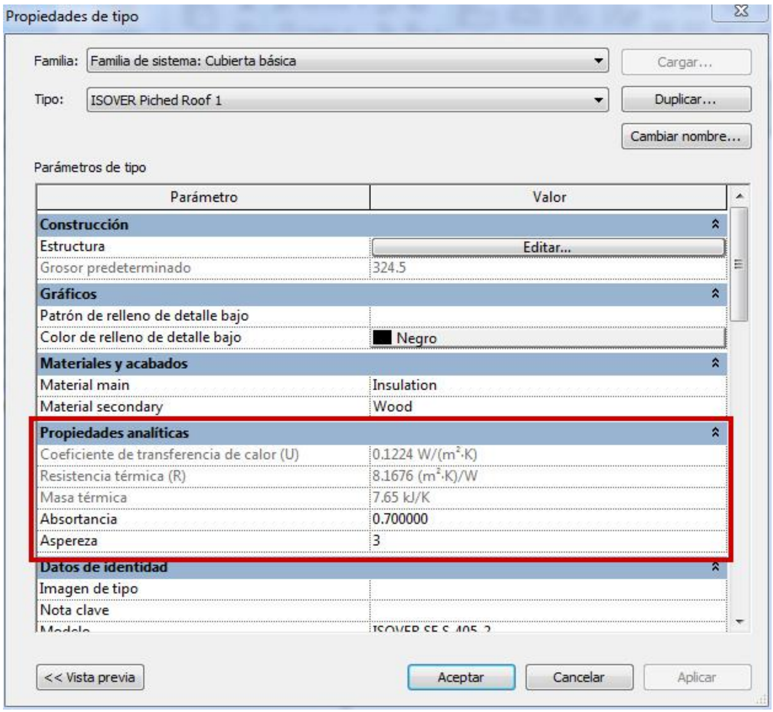


Figure 4.1: Parameters required for the calculation of thermal transmittance (courtesy of Agustí Jardí).

One of the benefits of having comprehensive information about the components of the BIM model is to get more accurate estimates of the project costs by having information about the availability of products and materials, conditions for their use, compatibility with other components or building systems, and the requirements for their transport and installation.

4.1.2. Parametric modelling

The concept of parametric modelling in the architecture field has been described by various authors in different ways[83]. For example, Eastman et al. (2011) define parametric modelling as the "primary technology that distinguishes the BIM design applications from earlier generation CAD systems" (Eastman et al., 2011). However, this concept is

[83] A brief history of parametric modelling can be found well documented in (Eastman et al., 2011).

not specific to the AEC industry since it is applied in many other fields, for example in the automotive and aerospace industries. Moreover, Aish, and Woodbury (2005) emphasized that parametric modelling is not a new concept in architectural design, since it has been applied for centuries. They claim that what is new is the supporting technologies for parametric design and mass production systems that benefit from it. Different authors (Stavric & Marina, 2011; Woodbury, Williamson, & Beesley, 2006; and others) have widely discussed about the application of parametric modelling in the architecture field. Some of them claim that the meaning of parametric modelling, and how it is implemented in software tools, is not clear.

Parametric modelling in architecture can be briefly described as a design form based on the assembly of 3D objects representing building components (walls, columns, beams, windows, pipes, etc.), where their geometry is defined by a set of parameters and rules. Some of these parameters and rules can be configured by users, while others, such as those defining the behaviour or which component can be connected to another, are defined by the data structure of each program. The parameters can be limited according to different criteria and rules. Some of these rules are intrinsic to modelling systems and enable the consistency of the model to be maintained, for example by automatically updating the parameter values according to a previously established behaviour. These updates may result from internal changes in the parameters of the object, or from changes in other objects that are propagated through the existing relations between them (e.g., the spatial relation between a column and a wall).

In BIM authoring tools, instances of each type of parametric object (columns, walls, windows, etc.) are defined with the same rules, so each of them has a standardized behaviour within the domain of the tool. The problem when trying to extract this standardization outside the domain of each tool lies in the different alternatives that exist to implement the same (or similar) behaviour. For example, the interaction between designers and the virtual model is conceived differently with each design tool. In addition, each tool encompass its own model of organization of information which responds to different design philosophies and certain ways of thinking and working of designers.

From a less technical perspective, one of the conflictive aspects most discussed in architecture is the extent to which parametric design poses a barrier for creativity. Cross (2006) refers to this creative aspect of design as a “journey to explore, to discover something new, rather than to return with yet another example of the already familiar” (Cross, 2006). Taking this definition as a reference, Davis (2013) argues that parametric models are prone to a lack of flexibility, making them fragile and breakable. This drawback can lead to a series of delays in practice requiring the most fragile parts to be rebuilt. Davis also claims that limitations in parametric modelling and inflexible models can become a barrier for collaboration and limit the creativity of designers. These limitations had already been observed by Eastman et al. (2011). They provided a list of the five main reasons why predefined objects in parametric modelling limit the design and manufacturing. First, different configurations of the components can be necessary depending on the discipline (e.g., the modelling of thermal breaks for windows can be necessary). Secondly, not all definitions of the components can be represented in the design (e.g., rooms with a domed ceiling). Thirdly, the structure and behaviours of building systems are not available in the design programs (e.g., building skin systems).

Fourthly, there are components not provided in the libraries of BIM authoring tools (e.g., photovoltaic systems). And finally, there are limitations in the extensibility of the objects in order to include extra detailing, attributes, etc. Other limitations can be found in objects that should respond to different patterns of behaviour. Different possible behaviours in an object lead to the complexity of having to deal with a large number of parameters and geometric constraints (Lee, Sacks, & Eastman, 2006).

Despite all these drawbacks, and when compared to the benefits described above, there is an increasing need of a building modelling based on the parameterization of the components, including the geometry, spatial relations, location and properties that compose the building, is needed to greatly facilitate the modelling task. Due to the increased demand for efficiency in building design, the smart behaviour derived from this parameterization is essential to speed up the design process. This same smart behaviour should enable a more automated design of a building without implying extra effort for designers. The benefits of this more automated design have started to grow quickly as architects, engineers and constructors have begun to work with parametric modelling software (Andia, 2013). However, some of these advantages are lost when information about the BIM model needs to be exchanged between BIM applications of different vendors. As stated in Chapter 2, this is a main problem for interoperability.

4.1.3. Product modelling

The term "product modelling" derives from the concept of parametric modelling introduced in the last section. In the context of the AEC industry, this term – and the subterms – has different meanings. While the subterm "product" (to be modelled) can refer to a (1) building or a (2) building component (which can be used in a building model), the subterm "modelling" (of a product), in turn, can be understood as (1) a process to design three-dimensional object components or buildings through a 3D graphical interface, or (2) a process to design conceptual data models for building descriptions using a data modelling tool. In the literature review, most authors (Björk & Penttilä, 1989; Eastman, 1999; and others) usually refer to the term "product modelling" as the process of modelling a building using design authoring tools, namely building product modelling, while few authors refer to it as the modelling of building components resulting in product models (e.g., Sacks & Eastman, 2014).

The term "product modelling" referring to the modelling of buildings first appeared in the context of the research project RATAS, started in 1985. In this project led by Bo-Christer Björk, a group of organizations and companies from the AEC industry in Finland were involved in defining a standard method for describing information about modern buildings (Björk, 2009). To achieve this aim, the term "product data model" was introduced, defined as "conceptual structures specifying what kind of information is used to describe buildings and how such information is structured" (Björk & Penttilä, 1989). Later, the concept of a building product data model was addressed by Björk (1995) in terms of the need to exchange data through the question: "How should we structure digital information describing a building in order to facilitate as much as possible, the exchange of information between the computing applications in construction which produce or utilise this data" (Björk, 1995). The need to find a standardized language for the construction of conceptual schemas was one of the first issues identified in this research.

For this purpose, some examples of conceptual schemas based on product data models described in the EXPRESS language were provided. Moreover, in his thesis "Requirements and information structures for building product data models" (1995), Björk defined a layered framework architecture where the information about building product data models is grouped in five levels: information modelling language, generic product description models, building kernel models, aspect models and application models. Later, Eastman (1999) redefined the concept of a building product model in the same terms as the BIM is known today (Afsari & Eastman, 2014).

However, the term product modelling can also be associated with the parametric modelling of building components. The issues related to this meaning of the term have been approached in literature through different conceptions. For example, Lee et al. (2006) focused on the issue of the behaviour in parametric building objects. From the conceptualization of the behaviour of these objects as "the ability of an object to respond to internal or external stimuli", they introduced the term "building object behaviour" (BOB) as the behaviour of a building object. They also developed a notation and description method for describing and validating parametric definitions of these objects in a reusable format.

4.1.4. Structural precast components

Structural components mainly include columns, girders, beams, slabs and hollow-core slabs. These are generally the most important components in the building design as they are the most affected by the design criteria and analysis. They are also subject to specific types of rules. The most important are those that define the connection between components in a structural system, and those that must be met to ensure the structural integrity of the building and which are defined in regulations.

The use and dimensioning of structural components in building projects are subject to structural analysis, which falls into the domain of structural engineering. The structural calculation is usually performed with specialized tools (e.g., Robot, Cypecad and Tricalc). These tools can be selected depending on the type of calculation to be performed and the type of structural components (e.g., steel, in situ concrete, precast concrete, wood). Moreover, there are also BIM authoring tools that are more adapted to facilitate the modelling of the structural design (e.g., Revit Structure and Tekla). Currently, most of the data exchange operations in BIM-based projects are performed between structural calculation and modelling applications.

For the particular case of precast concrete components, the main criterion applied when performing the structural calculation has to optimize the amount of concrete to meet the economic requirements of the project. This means selecting the smallest sections possible while complying with the safety regulations for structural integrity. However, this calculation process is not usually achieved in one single step. In many projects, this process requires several iterations between the design proposed by the architect and the solution proposed by the structural engineer.

The number of iterations in this process could be minimized if designers pre-dimensioned the components in the structural model. The aim is to facilitate a structural model which is as close as possible to the final solution. This requires the incorporation of the pre-dimensioned structural models information which enables the designer to check if the regulations are fulfilled. Providing this information in an automated manner is one of the objectives of this thesis.

4.1.5. The role of manufacturers

As we have seen, BIM-based projects can be developed through the assembly of two types of building component models (BIM objects): generic models of components, such as those provided by default in the library of BIM authoring tools, and specific models provided by the manufacturers. Both types of components can be downloaded from existing online libraries and catalogues. While designers are more likely to use generic models in the early stages of the design, in the advanced stages, manufacturer data can be included in the component models or can be replaced by product models. As a result of the growing demand to satisfy the second case, more and more manufacturers are providing BIM versions of their products published on the Web in different formats.

Bevill and Arsenault (2010) classified the reasons why manufacturers can obtain a benefit from this publication into three types:

1. **Changes in the methodologies of building projects:** Manufacturers are starting to realize that the construction sector is increasingly adopting BIM methodology in building projects. Therefore, they have to adapt to the new needs of the sector resulting from the implementation of this new methodology in order to remain competitive.
2. **Cover a new need:** Creating libraries of BIM objects for a specific project is a time-consuming task and often is not profitable for designers, architects and builders. BIM objects provided in online libraries, and in the web of manufacturers, enable agents to focus on the development of the building design instead of expending time on modelling the components.
3. **Up-to-date product information:** The products traded in the market may be changing, evolving and even disappear when they become obsolete or unmarketable. This situation can also occur when a particular rule or regulation is no longer met. At the same time, the need to keep updated information about products, providing new offers and new digital formats that may be needed in the BIM authoring tools, is paramount.

Information available about building products in the early stages of a building project allows designers to anticipate potential problems in its future construction. Other aspects include improving the overall quality, reducing waste and fulfilling timely delivery commitments to manufacturing planning and scheduling (Bevill & Arsenault, 2010). This information also facilitates evaluation of the characteristics of the products regarding their installation, commissioning, operation and maintenance, installation instructions, warranty management, training, etc. (Conover et al., 2009).

Beyond these benefits, the involvement of manufacturers from the beginning of the project may lead to obtaining more suitable solutions in accordance with the requirements of the project. For example, manufacturers may be able to better predict the production needs and provide the components through just-in-time delivery methods. Moreover, a real-time dialogue between designers and manufacturers may also make the creation of specific products for the project more feasible, as well as adapting the existing ones to the design criteria (Conover et al., 2009).

4.1.6. Decision support

Providing solutions for greater reuse of information about building components and products in BIM-based projects depends on the capacity to pre-process all the information that may be necessary for the development of a BIM model, so that it can be easily reused. By information that needs to be pre-processed we are referring to that which is normally provided, or defined, in formats that are not ready to be reused. This means that BIM users need to extract and collect, sometimes infer, this information manually. A typical example is when the information (e.g., regulations, technical data and data sheets) is provided in text documents, such as PDFs. To facilitate this process, the information should be pre-processed in some way (transformed, integrated, combined, etc.).

Reusing information also encompasses the hability to easily find products whose characteristics can make them valid to be used in the design of the building to be built. This capacity should be provided through methods capable of performing searches of products based on different features and criteria (dimensions, materials, prices, manufacturer's location, etc.). Support for the choice of products and materials for the building is a central issue in building projects. This choice is subject to a set of criteria that are related to the adequacy, consistency and durability of the materials for application in the building, as well as in terms of economic and social factors, design, workmanship and environmental conditions, for example.

In the market there is a wide range of building products and materials available. These can be selected, for example, by building designers with the objective of meeting the growing demand for quality in the built work. This implies being aware of direct requirements for the design and modelling of a building, energy efficiency, etc., but also meeting regulations, codes and laws. To fill this gap, decision-support tools embedded in BIM applications can help facilitate the choice of these products in the design stage. These same tools can support decision-making based on their information once introduced into the BIM model.

The main problem with decision-support tools in BIM applications is that they contain limited and not updated information about the current existing products in the market. There is a large number of situations in the development of building projects that require support for decision-making. Cases in which this support is not provided by BIM applications lead to third parties developing decision-making systems and prototypes to satisfy the needs. Several examples can be found both for commercial purposes and developed within the research field. Many of the examples found are focused on providing this support for the choice of sustainable materials and products. For example, Bank, Thompson, and McCarthy (2011) developed a workflow to link the data within

BIM models to what they call a "system dynamics decision-making model"[84]. They applied this model in a decision-making framework for the selection of sustainable materials Linking the AnyLogic and the Revit tools (via plug-in). Moreover, the authors argue that by linking tools, for example, a BIM model to an energy model, the leadership in the energy and environmental design (LEED) accreditation process would be more efficient (Bank et al., 2011).

Another case of decision-making systems was proposed by Ogunkah and Yang (2013). They developed a multi-criteria Decision Support System (DSS) intended to assist in the selection of low-cost green building materials. The system is based on key influential factors that are used to measure the suitability of the materials. Based on these factors, the system provides useful and explicit information to assist designers in the selection of materials in the early stages of the design. They indicated that one of the biggest problems in the existing decision-making systems is the availability of the data – in this case, about low-cost green building materials – which are often very large, complex and not organized in formats that facilitate the extraction of meaningful information. This situation often leads to requiring the help of experts in databases. As an alternative, they proposed a method based on a set of macros in spreadsheets in which they apply the AHP (Analytic Hierarchy Process) technique in order to reduce a range of alternative materials available to a short manageable list of a few technically viable options.

In spite of the improvements provided by these implementations, most of them still have to face the common problem related to the availability of the data, and also their reuse to facilitate more open and standardized approaches. This refers to solutions in which third parties can reuse information. This way, solutions can be adapted to solve specific problems regardless of how the data are defined or provided.

In Chapter 3, the benefits of Semantic Web technologies were discussed in terms of their use in providing information in open formats (RDF/OWL), with more capacity to infer its meaning. Also, in Section 3.3, the advantages of the use of these formats for data integration processes were discussed. Information about materials and products available in these formats and applications for its integration should be able to provide better solutions for decision-making in their choice. Examples of these applications have not been found, mainly because there is not yet any information available in this domain provided in Semantic Web formats. Nevertheless, the validity of this use has been proven in other domains, for example in the energy efficiency of buildings. An example of where these technologies have been applied to assist in decision-making is the research project OPTIMUS, introduced in Section 3.3.5.

[84] System dynamics is a "modelling method that allows a system (in this case a building) to be represented as a feedback system using a set of differential algebraic equations representing the various sub-systems of the building and represented by a diagram consisting of stock, flow, and auxiliary variables" (Bank et al., 2011).

4.2. BIM product catalogues

Catalogues of products and materials are consulted during the building design and pre-construction stages, since most decisions about their choice are taken in these stages. Since 3D parametric object representations of components are required in the development of BIM models, some kind of catalogues and libraries needs to be provided. These 3D objects are referred to in the literature by several names depending on the context. For example, they are referred to as building object models (sometimes abbreviated to BOMs), object models of products, BIM objects, BIM components and so on. Sometimes this naming can be confusing since a building can also be considered, in turn, an object or a product.

4.2.1. Building product models

BIM models are made up of 3D parametric objects (BIM objects) representing physical building components (columns, beams, slabs, walls, doors, windows, etc.). BIM models can be enhanced and enriched with external information from other ecosystems and data sources (product catalogues, libraries of design elements, public procurement requirements, etc.). The capacity to reuse this information in the development of BIM depends on its availability and the format in which it is defined.

Currently, BIM authoring tools are providing generic versions of BIM objects by default in their internal libraries. Some authors call these libraries “BIM Content Libraries” (Afsari & Eastman, 2014). These objects are usually disconnected from any manufacturer source or product database. This situation leads to designers and architects seeking BIM objects corresponding to building products outside of these tools, when necessary. BIM objects can be downloaded from online catalogues and libraries on the Web and inserted into BIM models. A more direct alternative to facilitate this process is through plug-ins designed for BIM authoring tools implemented to this end. Usually these plugins are provided by online commercial platforms (e.g., BIM Object[85]), BIM libraries supplied by public and private institutions (e.g., NBS National BIM Library[86]), and large manufacturers (e.g., Hilti[87]).

The use of BIM objects representing building products is subject to various drawbacks. For example, a good quality of objects is not always guaranteed, and the information they include is often poor, incomplete and not linked to other data sources. Part of these problems can be attributed to the lack of mechanisms to allow manufacturers to define this information by themselves. The production of high-quality BIM objects requires some knowledge, resources and skills combined with expertise in providing the product information (geometry, costs, structural data, waste, etc.) required for a particular project. Since this is presented as a complex task, manufacturers are turning to consultants, specialized companies and professionals for their development. However, they are not

[85] BIM Object. Retrieved from http://www.bimobject.com/.
[86] NBS National BIM Library. Retrieved from https://www.nationalbimlibrary.com/.
[87] Hilti. Retrieved from https://www.hilti.es/medias/sys_master/h67/h23/9092742742046/Revit.pdf.

always aware of the requirements associated with their final use. Therefore, one of the challenges here is to provide consistent definitions of object models for products capable of satisfying the different uses identified for each stage of the design (Eastman et al., 2011). This will require the provision of different levels of definition in order to meet each type of requirement (e.g., according to the LOD required in a specific stage).

To enable the reusability of BIM objects from external libraries or catalogues within BIM authoring tools, different conditions need to be met. Eastman et al. (2011) state that four aspects must be considered for proper interpretation of these objects within BIM authoring tools: “object classification, naming conventions, attribute structure, and possibly the designation of topological interfaces with other objects reflected”. Among the issues underlying these aspects, the mappings between native objects and common definitions of them are the most critical factor. Another issue to be considered is the use of standard classifications as a means to facilitate the management of these objects during the design according to the project specifications (e.g., Uniclass 2015 enables the information to be organized according to element types, systems or elements defined by different parts, and product specifications, among other uses) (see Section 2.3.7). The use of classifications enables information (properties) required in building object models to be associated according to specific purposes (Eastman et al., 2011). As a result, these objects can be sorted and searched according to these properties (Ekholm & Häggström, 2011).

4.2.2. Existing building product catalogues

As part of this research, different examples of the most commonly used commercial catalogues of BIM objects have been examined in order to assess their main features. These catalogues are:

- Autodesk Seek[88]. Online catalogue created by Autodesk to search, share, and download BIM objects, generic or representing products of different manufacturers. Associated information (e.g., technical details) can also be downloaded. BIM objects are provided in Autodesk formats (Revit, Autocad, etc.) and IFC.
- BIM Object. The most used online catalogue of products which includes more than 43,000 objects (at the time of carrying out this study). BIM Object provides different tools and services to facilitate reusing BIM objects in the BIM modelling. Moreover, this is the catalogue that includes the most references about classification systems for each product.
- Bimetica. Another catalogue of BIM objects. Most users of this catalogue are currently from Spain and South America. Its main current lack is that it does not provide any plugin to facilitate the reuse of BIM objects.

[88] Autodesk Seek. Retrieved from http://seek.autodesk.com.

- BIM Components. An online catalogue specifically for BIM objects for the Archicad design tool. Since the web of the catalogue is also a community portal, some product references are linked to other (external) catalogues (e.g., BIM Object).
- BIM Catalogs[89]. A web portal with BIM objects of different manufacturers available in a large number of formats. However, despite offering an application to allow users to consult the catalogue from mobiles and tablets, they are not offering any plug-in to facilitate the reuse of BIM objects within the BIM authoring tools.
- Sweets[90]. An online catalogue that provides BIM objects of building products, among other information about them (CAD files, specs, etc.). Currently, the BIM objects are only available in Revit format.
- NBS National BIM Library. An online BIM object library developed and maintained by the Royal Institute of British Architects (RIBA) in the United Kingdom. Therefore, the main users of this library are professionals from this country.

We have analysed these catalogues and identified their capabilities to provide generic BIM objects, product specific BIM objects, components in proprietary BIM formats, available plug-ins, and adherence to product classifications. Note that none of the catalogues examined provides BIM objects with different LODs. Figure 4.2 shows the results obtained from the analysis.

[89] BIM Catalogs. Retrieved from https://bimcatalogs.partcommunity.com

[90] Sweets. Retrieved from http://sweets.construction.com.

Catalogues	Generic BIM objects	Manufacturer's BIM objects	BIM authoring tools	Formats	Plug-ins available	Standard Classifications (Web page)
Autodesk Seek	Yes	Yes	Revit, Autocad	.rfa, .dwg	integrated to Revit	None
BIM Object	No	Yes	Revit, Vectorworks, Archicad, AECOsim, Autocad, SketchUp, Tekla, IFC	.rfa, .rvt, .pln, .xml, .xsd, .dwg, .skp, .ifc	SketchUp, Revit, Archicad, and Autocad	Multiple
Bimetica	Yes	Yes	Revit, Archicad, AECOsim, IFC	.rfa, .rvt, .pln, .xml, .xsd, . Ifc	No	None
BIM Components	Yes	Yes	Archicad	.pln	integrated to Archicad	None
BIM Catalogs	No	Yes	Revit, Vectorworks, Archicad, AECOsim, Autocad, SketchUp, Tekla, IFC	.rfa, .rvt, .pln, .xml, .xsd, .dwg, .skp, .ifc	No	IFC
Sweets	No	Yes	Revit	.rfa	Revit	MasterFormat
NBS National BIM Library	Yes	Yes	Revit, Vectorworks, AECOsim, Archicad, Tekla, IFC	.rfa, .rvt, b.xml, .xsd, .pln, .ifc	Revit, Archicad	Multiple

Figure 4.2: Comparison between different BIM catalogues and libraries.

A survey about the use of BIM product catalogues was conducted in the context of this research in collaboration with members of the BIM user group of Catalonia (Costa et al., 2016). The survey was carried out from January to February 2016. More than one hundred AEC professionals in Spain answered the questionnaires. One of the questions of the survey asked the participants about the use of product catalogues with the following results: BIM Object (47.6%), Bimetica (30.5%), Autodesk Seek (30.5%), NBS (National BIM Library) (19.1%), BIM Components (Graphisoft) (18.1%), BIM Bandit (2.9%). Another finding of the survey was that 27% of surveyed users do not use BIM objects downloaded from external catalogues to build their designs. The remaining 73% download BIM objects from online catalogues to create their models. From this group, most of them (51%) use both types of BIM objects (generic and based on manufacturers' products) while only 14% use generic BIM objects.

Another observation from this review is that even when there are some BIM objects provided in the IFC standard in these catalogues, most of them are provided in proprietary formats. This is due to two main factors. On the one hand, the IFC standard, along with all buildingSMART technologies is in many cases not capable to represent the BIM objects with the geometric and parametric quality required. Only simple objects can guarantee this. On the other hand, even when this quality can be supported by the standard in some objects, not all BIM users have the confidence that the BIM authoring program they use will be able to interpret it correctly. Moreover, to improve the efficiency in the use of these catalogues, more efforts should be focused on unifying the criteria in the classification and categorization of products (Afsari & Eastman, 2014).

While large and medium-sized manufacturers have BIM object representations of their products in the catalogue platforms examined, or even in their own websites, this is not so common in the case of small companies. Having representations of BIM objects of products requires from manufacturers an investment to create and maintain them.

4.2.3. Open semantic building product catalogues

As we see above, digital product catalogues, in particular those that provide BIM objects, are becoming central in the development of BIM-based projects. Given that one of the central issues in improving the BIM modelling lies in having a better control of the semantics of the information, part of the research has focused on the use of ontologies and the Semantic Web technologies in building product catalogues.

Since the IFC standard is presented as the best way for sharing common representations of BIM models, some of the research in finding new forms of catalogues has focused on solutions based on this standard. Some authors have proposed methods and solutions to facilitate reusing of component models in this format. For example, in Section 3.2.5 we described the prototype proposed by Beetz and de Vries (2009) implemented for distributed heterogeneous product catalogues using Semantic Web technologies. This prototype was based on a lightweight ontology created with IFD concepts. The ontology was designed to capture the information about products in a common metadata model composed of four layers. Through this model, information about products can be published in the RDFa format (Herman, Adida, Sporny, & Birbeck, 2015) on the website of the manufacturer, making it machine-accessible.

Other solutions have been developed outside the IFC standard. For example, Jain and Augenbroe (2003) proposed a methodology to facilitate the choice of building products based on their performance according to the conditions of the design. In their approach, they considered aspects such as the difficulty in obtaining a standardization in the data of the manufacturers since “it puts an added burden on the manufacturers to restructure their databases to standard formats” (Jain & Augenbroe, 2003). They also indicated the difficulty to deal with the choice of building products when the number of catalogues of manufacturers increases every day. To address these issues and others related to searching methods provided in other methodologies, they proposed a querying system through bcXML format (Lima et al., 2003). The authors devised a functional taxonomy and standardized mapping functions to provide a communication between a service developed to assist designers in selecting products and various product catalogues of manufacturers using this method.

In the context of the solutions based on ontologies and Semantic Web technologies, Böhms (2007) proposed a Semantic Web-based Open engineering Platform (SWOP) which enables the specification of products to suit the requirements of the end-users (Böhms et al., 2009). At the core of the platform there is a generic, reusable, upper ontology for product modelling called PMO (Product Modelling Ontology). This ontology was specified in OWL and extended to four domains (product, representation, rule and operation) to fulfil the different types of requirements for the product modelling.

The application of ontologies for the development of intelligent building product catalogues was also investigated by Semenov, Gonahchan, Morozov, and Tarlapan

(2014) in the context of the research project ISES (ISES, 2014). After a review of the possible existing ontologies that could be used to create the catalogues, the authors argued that none of them satisfy the requirements for this purpose (Semenov et al., 2014). For this reason, they proposed a new product ontology in order to satisfy complementary features (e.g., providing compatibility with IFC/bSDD standards and a minimum level of interoperability with third-party catalogues). The ontology model was developed in the EXPRESS language and designed to keep the compromise between management and reasoning capabilities.

In conclusion, most of the research conducted in the area of product catalogues for BIM modelling is intended to provide methods to improve the reuse of this information. However, it seems that they do not facilitate the specification of this information by the manufacturers. One of the goals of the research project BAUKOM, introduced in the next section, was to fill this gap.

4.3. The BAUKOM Catalogue

4.3.1. Introduction

The BAUKOM project was the result of one of the research lines followed by the research group ARC Enginyeria i Arquitectura La Salle, and was aimed at developing new online catalogues of building products for the AEC industry using Semantic Web technologies. This line of research was initiated within the research project BARCODE HOUSING SYSTEM[91] (Madrazo, Sicilia, González, & Martin, 2009). In this project, a product catalogue was developed in order to enable manufacturers to set up models of their products based on templates designed according to each type of component. The configuration included properties such as those relating to materials, dimensions and the behaviour of components within a real-time 3D engine designed for virtual representation of dwellings. Information about components was stored in a graphic schema defined in XML.

This research line was continued in the development of the BAUKOM catalogue (Costa & Madrazo, 2014, 2015), a project carried out by the ARC research group in collaboration with a precast concrete company – PRECAT Hormigones Prefabricados de Catalunya– with the support of the Spanish National RDI plan. The result of this project was a catalogue of building components based on precast concrete products integrated in ABEA, a commercial platform in the cloud. Semantic Web technologies and ontology engineering were applied in the development of this catalogue to create semantic descriptions of these types of building components with different levels of expression.

This project arose from the need to create an online platform to help improve the processes of design, manufacturing and marketing of prefabricated concrete structural

[91] The research project BARCODE HOUSING SYSTEM (BCHS) was carried out from 2005 to 2009 with the co-financing of the Spanish National RDI plan. Retrieved from http://www.barcodehousing.net.

components, under the challenge of greater industrialization in order to respond to industrial demands in terms of quality, sustainability and adaptability. Based on this premise, the research in this project was conducted in two main directions. On the one hand, a method was proposed to allow manufacturers to define different information about their products as parametric data. On the other hand, a data integration process was devised to combine the information defined by the manufacturers with other heterogeneous data sources.

The aim of this integration process was to provide a unified view of information about building components and products as a resource on the Web. This way, third parties may be able to reuse this information adapted to their needs. For example, software developers can create services and applications to assist in the use and choice of components and products for the BIM modelling. These services and applications can be implemented as services on the Web, desktop applications or plug-ins for BIM authoring tools. Since the information of the catalogue is available in Semantic Web formats, in this case provided through a SPARQL endpoint, they can be used to invoke reasoning processes.

In order to provide this data integration process and its reuse in the BIM modelling, an information system architecture was developed to interlink (1) building product catalogues, (2) associated services and (3) BIM software. Figure 4.3 shows the relationship between these three components. In this architecture, an ontology was developed to integrate information about building components provided by product manufacturers and other available data sources from different domains (Costa & Madrazo, 2015).

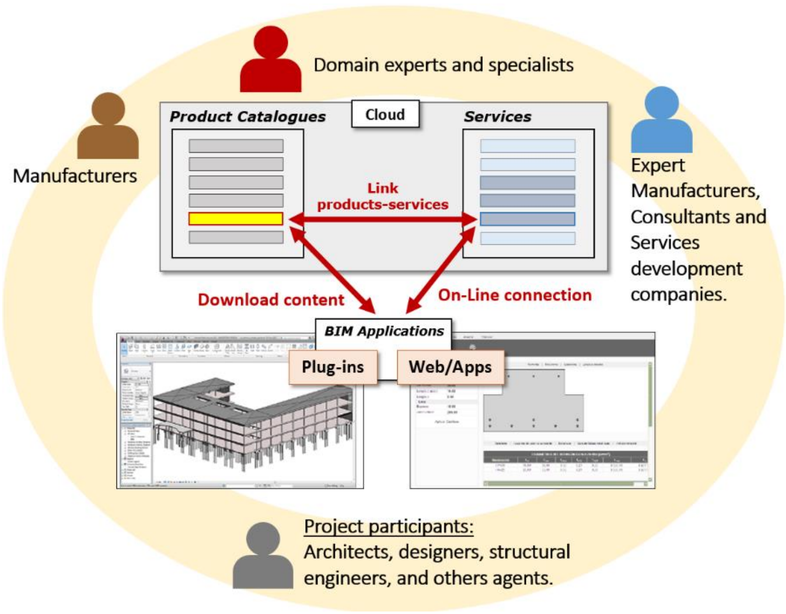


Figure 4.3: Structure of the BAUKOM project showing the connection between product catalogues, services and the BIM software (Costa & Madrazo, 2015).

The catalogue was tested with four types of structural precast concrete components (beams, columns and corbels). However, any type of component can be described through the approach proposed in the architecture developed. This architecture is described below.

4.3.2. Architecture

The architecture of the information system developed in BAUKOM is composed of four interlinked modules. These modules provide the necessary infrastructure to integrate and combine building product information: (a) integration of data related to the domain of building components (Section 4.3.3), (b) specification of building product data models (Section 4.3.4), (c) linking data from different domains (Section 4.3.5) and (d) services for BIM applications (Section 4.3.6). Figure 4.4 shows the interconnection between these modules and how the information flows through them over three stages: (1) data integration, (2) data linking and (3) data exploitation. The modules and stages depicted in the figure are described below.

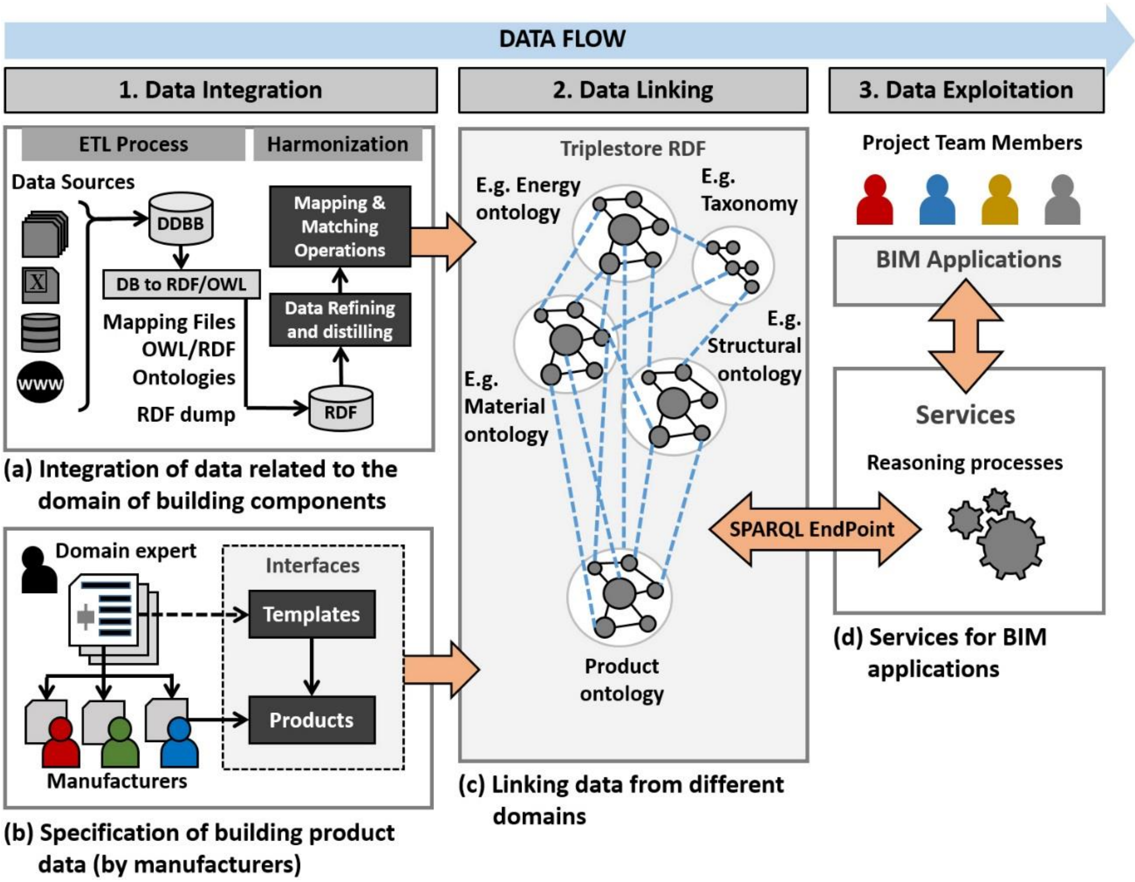


Figure 4.4: Overview of the BAUKOM catalogue architecture (Costa & Madrazo, 2014).

4.3.3. Integration of data related to the domain of building components

Currently, the information about building components is dispersed in different information systems and data formats (e.g., files, HTML pages, Excel documents, data bases, and web services). There is even information that has not yet been digitized (e.g., handbooks, manuals, and regulations). In addition, this information is not explicitly described. Consequently, agents of the construction sector have to carry out cumbersome processes to collect and validate each of the aspects that should be considered for the choice of components and products in projects. With the aim of providing a solution to alleviate this problem, Semantic Web technologies were investigated to provide a data integration method to transform the information from different heterogeneous data sources into a common language.

In Chapter 3, Section 3.3, different data integration methods based on Semantic Web technologies were introduced, one of them based on the integration of the data residing in relational databases. In the case of BAUKOM catalogue, the proposed data integration method consists of an ETL process divided in three steps: (1) data extraction from a relational database into RDF format using direct mapping[92] techniques, (2) data refining/distilling, and (3) mapping and matching operations. Previous to the application of the data integration process, the information available in various data sources and formats (documents, spreadsheets, databases, handbooks, etc.) is extracted and stored in an intermediate relational database with the aim of standardizing the subsequent data integration process. As such, two processes can be performed independently: (1) data insertion into the database and (2) data integration. Consequently, the staff involved in the first process do not require technical knowledge about ontologies, while the second process can be semi-automatically carried out. In some cases, the first process may require the development of ad-hoc tools to facilitate the data insertion, for example, when the data comes from spreadsheets.

In the first step of the second process – the data integration process – the data are extracted from the database and transformed into the RDF format using direct mapping techniques. In this case, the D2RQ tool (Bizer & Seaborne, 2004) is used to obtain mappings defined in the D2RQ mapping language. In the second step, these mappings are aligned according to the corresponding extension of the BAUKOM ontology used to represent these data. Finally, the mappings are used in the third step to transform the data into RDF using the D2R Server tool (Bizer & Cyganiak, 2006), and store them into a triple store (e.g., OpenLink Virtuoso Server).

This data integration method (Figure 4.4a) can be used to integrate various classification systems. To verify its feasibility, it was applied to MasterFormat[93], a standard classification described in Section 2.3.7. As other classification systems, MasterFormat includes a list of categories divided into numbered sections. The data integration process starts by defining a version of the classification in an Excel file. In the next step, the file is loaded into an application that was created to facilitate the insertion of classification systems from Excel spreadsheets into a SQL server database. Once inserted, the data integration process is performed in three stages. First, direct mappings are generated using the D2RQ tool (Listing 4.1Listing 4.1). Second, the mappings are refined according to the vocabulary defined in the BAUKOM ontology, and unrequired mappings are removed. Finally, the data from the database corresponding to the taxonomy model are transformed into RDF (Listing 4.2 and Listing 4.3). A simple Java tool was developed to enable ontology engineers to carry out this process.

```
generate-mapping -o mapping.ttl -u db-user -p db-password
jdbc:url://DatabaseInstance:port;DatabaseName=Name
```

[92] Arenas, Bertails, Prud'hommeaux, and Sequeda (2011). Retrieved from https://www.w3.org/TR/rdb-direct-mapping/.

[93] The specification of MasterFormat. Retrieved from http://csinet.org/numbersandtitles/.

Listing 4.1: Instruction to generate mapping files using D2RQ.

```
d2r-server mapping.ttl
```

Listing 4.2: Instruction to start D2R server to enable SPAQRL queries to the database.

```
dump-rdf -f TURTLE -b http://localhost:2020/ -o instances.ttl
mapping.ttl
```

Listing 4.3: Instruction to generate the RDF data (instances) using D2RQ.

Having the data of the MasterFormat classification system integrated into the BAUKOM catalogue, manufacturers can then assign one or more of its categories when they are introducing the information of their products. In this way, end users may be able to perform searches of products by categories. These searches can be performed in SPARQL by adding the corresponding relation with the category name in the query.

Other data sources can be integrated following the same ETL process. The implementation of a (materialized) data transformation was preferred to the virtual one for several reasons. With the exception of information about commercial products, the data related to the domain of the building components (classification systems, general features, handbooks, building codes, etc.) is not frequently updated. Moreover, having all the data integrated into a single data system provides greater reliability. Finally, the possibility was considered of including information in the future that does not have to be provided in a database (e.g., information provided in RDF).

4.3.4. Specification of building product data

The catalogue includes a set of interfaces to create different product data templates. Once created by specialists and published in the catalogue website, product data templates can be searched and selected by manufacturers to use them to describe their products. This results in a two-level structure of the data organization as shown in Figure 4.4b. Templates can be created, for example, based on existing common product data sheets (Figure 4.5). In this creation process, different units can be selected for each parameter (e.g., length, area, volume). Each type of unit is linked to a magnitude, for example the "length" unit is linked to the metric magnitude, in this case represented in millimetres. More information about the product definition process can be found in Costa and Madrazo (2014).

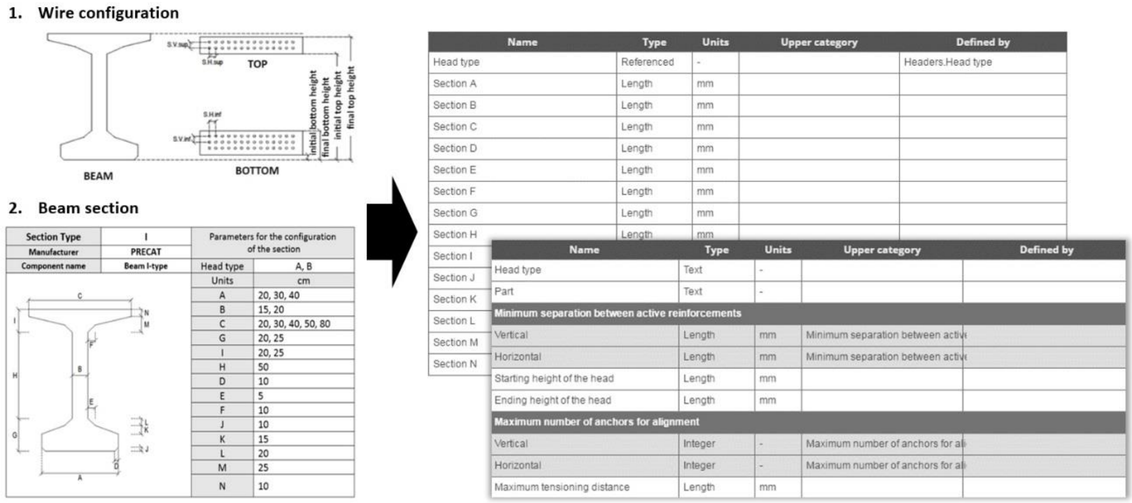


Figure 4.5: Interface to define objects for product templates (Costa & Madrazo, 2015).

4.3.5. Semantic data integration process

The information about templates and associated products created in the BAUKOM catalogue is stored in a relational database. This information is transformed into RDF to enable the combination of this information with information about building components and products, and to make it available in Semantic Web formats on the Web. The process is performed every time that a new template or product is defined in the catalogue by a user (e.g., manufacturer). An ontology was created in OWL to represent the information of templates and products (Figure 4.4c) with the name ‘product ontology’. Its design started with an RDF graph generated from the schema of the BAUKOM catalogue relational database. This graph was obtained through a functionality available in the D2RQ tool (Listing 4.4). Then, the ontology was completed with the use of Protégé ontology editor.

```
generate-mapping -o schema.ttl –v -u db-user -p db-password
jdbc:url://DatabaseInstance:port;DatabaseName=Name
```

Listing 4.4: Instruction to generate a RDF graph using D2RQ tool.

To facilitate a better understanding of the definition of the data specified in the ontology by third parties, concepts and parts of other existing ontologies were reused as much as possible. For example, some concepts of the ontology of units of measure (OM) (Rijgersberg, van Assem, & Top, 2013) were included to represent the values of product parameters with the corresponding associated units. This ontology was chosen because it is published on the web and includes an exact definition of the units provided in the catalogue.

Other ontologies related to the domain of product catalogues, such as GoodRelations (Hepp, 2008), were considered and then discarded. The GoodRelations ontology focuses on e-Business (offers, legal entities, prices, terms and conditions, etc.) rather than on product information. For this reason in BAUKOM, it has been necessary to create a general method to describe any product-related feature through different levels of expression.

The resulting ontology of the catalogue was verified to ensure its correct definition using the W3C RDF validation service (Prud'hommeaux & Lee, 2004) and the OntOlogy Pitfall Scanner (OOPS) (Poveda-Villalón, 2016).

4.3.6. Services

Product-related information in BAUKOM catalogue is available in RDF through a SPARQL endpoint (Figure 4.4d). Taking this into account, various services were developed in which information from the catalogue is accessed to assist in different situations of the BIM modelling. For example, in (Costa & Madrazo, 2014) a service for calculating the dimensioning of beams was introduced. The service carries out queries in the catalogue to retrieve information about products corresponding to beams. In particular, necessary information for the structural calculation is retrieved from all instances of a template of this type of component. The template is previously selected from a list of templates that can exist within the "beam" category. This way, information about products created using this template can be filtered for the calculation based on different criteria (weight, amount of material, price, among others). The user of this service is a structural engineer who will use the component in a specific building project. Therefore, the distance between columns where the beam must be placed, and the connectivity with the other structural components, are other limiting factors that can be defined in the service. Figure 4.6 shows the interface of this service.

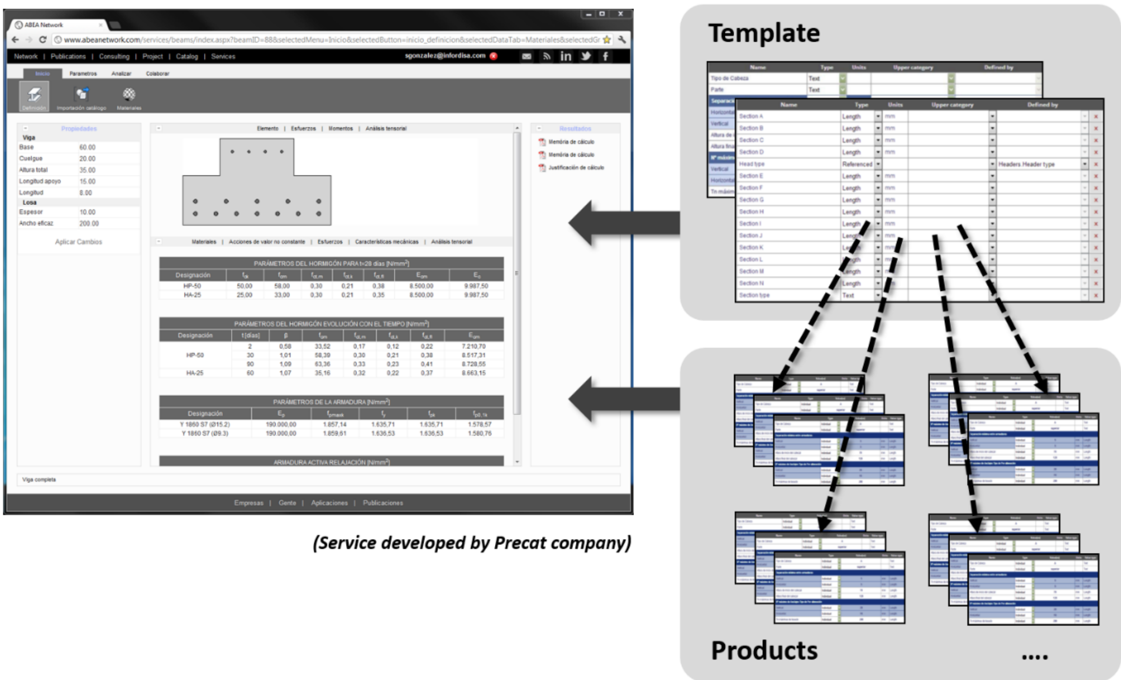


Figure 4.6: A service to calculate beams.

Another service developed as a plug-in for Autodesk Revit was introduced by Costa and Madrazo (2015). The service enables the design team to be assisted in the process of selecting precast concrete beam products that suit the project requirements.

4.4. Summary and conclusion

In this chapter, it was investigated the extent to which Semantic Web technologies can be applied to integrate data related to the domain of building components and products and to facilitate their automatic processing on a semantic level. To address this question, this chapter started by analysing the requirements of the information about building components and products for BIM modelling, as well as the main limitations and shortcomings of the information and the role of manufacturers in their provision. Then, the extent to which the Semantic Web technologies introduced in Chapter 3 could be useful to overcome some of these limitations and shortcomings was examined. To this aim, the research focused on two areas: the processes to enable manufacturers to facilitate information of their products which could then be used in BIM modelling, the integration of building product data with other data available in the Web using linked data.

Nowadays, information related to the domain of building components is found dispersed and defined in different information systems and data formats (e.g., files, HTML pages, Excel documents, data bases, and Web services). There is even information that has not yet been digitized (e.g., handbooks, manuals, and regulations). The search, access and retrieval of this information by the agents of the construction sector involved in building projects is usually a cumbersome process. For example, it is not easy to identify dependencies that may exist between each type of information and project requirements. Moreover, agents currently lack quick and guided access to the information required for decision-making, especially the information related to materials and products for construction. Consequently, it is difficult for them to quickly reach an optimal and valid solution for the design based on accurate and sufficient information. Methods and solutions have been proposed in the last few years to assist in the choice of green products and materials for more ecological and sustainable building construction. However, they are not generic enough since most of them are limited to a specific domain and geographic area.

Some building components and products are currently facilitated as BIM objects. As stated in Chapter 2, one of the major changes in designing with BIM compared to CAD systems lies in the use of 3D parametric objects. Hence, a BIM model is most of all the result of the assembly of different 3D parametric components (BIM objects). But this is not enough. To carry out the different tasks in BIM modelling efficiently, these parametric objects must contain additional information, for example, the information required to make a choice between alternatives or to perform some type of calculation.

Generic representations of building components are usually available in the libraries of BIM authoring tools, ready to be used in a design. Most of these tools also permit the inclusion of BIM objects external to them. BIM objects modelled to represent the behaviour of real products, through their parametrization and associated information, can be downloaded from manufacturers' websites. Section 4.2 reviewed the information and features about building products that are currently provided in the most popular catalogues and libraries of BIM objects on the Web, including a comparison of formats, services and other features provided in them. From this review, it can be concluded that these are very limited in offering BIM objects with customized information (e.g., depending on the discipline, LOD, location, etc.). Moreover, representations of BIM objects in open standard formats such as IFC are poorly present in most catalogues and libraries. Typically, BIM objects are facilitated as unique models for a small set of proprietary formats, since they are more reliable than IFC. However, these can only be used by the application for which they have been created.

The lack of information external of BIM objects available in proprietary formats makes it difficult to query their content to answer specific user and service requirements. The search for suitable building components for a project may require taking into account information about regulations to which they are subjected, quality certificates, embodied energy used in their manufacturing, performance with regard to energy efficiency and acoustics, and so on.

Finally, it was also observed that BIM objects representing products of small manufacturers are rarely found in the online catalogues and libraries of BIM objects. The investment and resources that must be provided by the manufacturers for their creation and maintenance represent a limitation for small companies. As for the large manufacturers, they often resort to subcontracting the modelling of their products. However, this can be a limitation since their experience and knowledge are not applied in the creation of the BIM objects of their products. This panorama led to the conclusion that new mechanisms are necessary to make it easier for manufacturers to define the information of their products by themselves. Likewise, methods and tools are needed to facilitate the integration of product information with other information related to the domain of building components. To this aim, the use of data integration methods based on Semantic Web technologies was explored. Data related to this domain integrated and provided on the Web can make it easier for agents involved in a building project to search and reuse them through services created to support BIM modelling activities. By publishing the information in Semantic Web formats, services can be developed taking advantage of the capabilities provided by these technologies, for example, by applying reasoning algorithms, rule-checking, and semantic federated queries over different RDF Web resources. All these benefits, together with the need for a means to enable manufacturers to define their products by themselves, led to propose the development of the BAUKOM product catalogue, introduced in Section 4.3.

The involvement of manufacturers in the definition of their products is necessary for a more efficient BIM modelling. They are experts who know about their products and their performance, a knowledge which is relevant in the design, construction and even in the maintenance stage. In the BAUKOM catalogue, a uniform data model of building components has been created using templates designed in collaboration with product experts (e.g., manufacturers) and other consultants (Figure 4.4b). Through this uniformity, software developers of BIM services can create solutions independently of the product brand, since the product information is described according to a generic RDF structure.

As part of the development of the BAUKOM catalogue platform, a data integration method to integrate domain-related data about building components from multiple heterogeneous sources was described in Section 4.3.3. As indicated in Section 4.3.3, information related to the domain of building components is not integrated and defined in different information systems and data formats (e.g., files, HTML pages, Excel documents, data bases, and web services), and some has not yet even been digitized (e.g., handbooks, manuals, and regulations). Taking this into account, the proposed method was designed to enable the representation of this information through a domain ontology that can be extended to integrate the information from new data sources as needed. The method is divided into two parts. First, the information from a source format is transformed in a common domain, in this case a relational database model. Second, the data is integrated according to an ontology. This requires extracting the data from the database and transforming them into RDF according to a single view schema – BAUKOM ontology – previously extended to include the new representation of the data. In Section 4.3.3, an ETL process using direct mappings and refinement techniques was described. To understand the process, we showed a simple example carried out with the MasterFormat classification system.

A materialized integration approach has been chosen because most of data sources of this domain are not updated very often (classification systems, general features, handbooks, building codes, etc.). However, this might not be the case if each time a new product is published in the catalogue this needs to be updated. Furthermore, this approach assures a greater reliability as a result of having all the data in the same data storage system. Finally, it was pointed out that in the case that new data directly provided in RDF have to be integrated in the future, materialized integration is more flexible than data virtualization.

Techniques and tools applied in the data integration method developed in BAUKOM are based on those already applied in other fields (e.g., Biology, Geology and Medicine), to resolve the heterogeneity among data residing in different sources. However, despite the semi-automation provided in the mapping generation, significant manual labour it still necessary. Today's relational-to-ontology mapping techniques are not able to provide a universal solution for the mappings, and most of the time they still require the intervention of domain experts to verify and complete them. Therefore, the role of experts is fundamental to carry out a semantic integration process.

Finally, although the system developed in BAUKOM meets the intended objectives, it was observed that there are situations in which the manual insertion of the data by the manufacturers can be a cumbersome process when the information is too comprehensive (e.g., large lists of ratios and coefficient values required for calculation). To avoid this manual process, and considering that most of the existing product information resides in the relational databases of manufacturers, a future line of research should focus on extending the current data integration method proposed to include its access. For example, this could be provided through a connector compatible with the template-product model implemented in BAUKOM. In this sense, it would be necessary to analyse to which extent the data need to be materialized in a triple store or, on the contrary, be provided through a virtualization approach. As for the last alternative, an analysis of the compatibility of the information systems currently used by manufacturers with Internet should be carried out.

The solution presented in the context of project BAUKOM involves the first part of the case study documented in this research. Figure 4.7 shows this part highlighted.

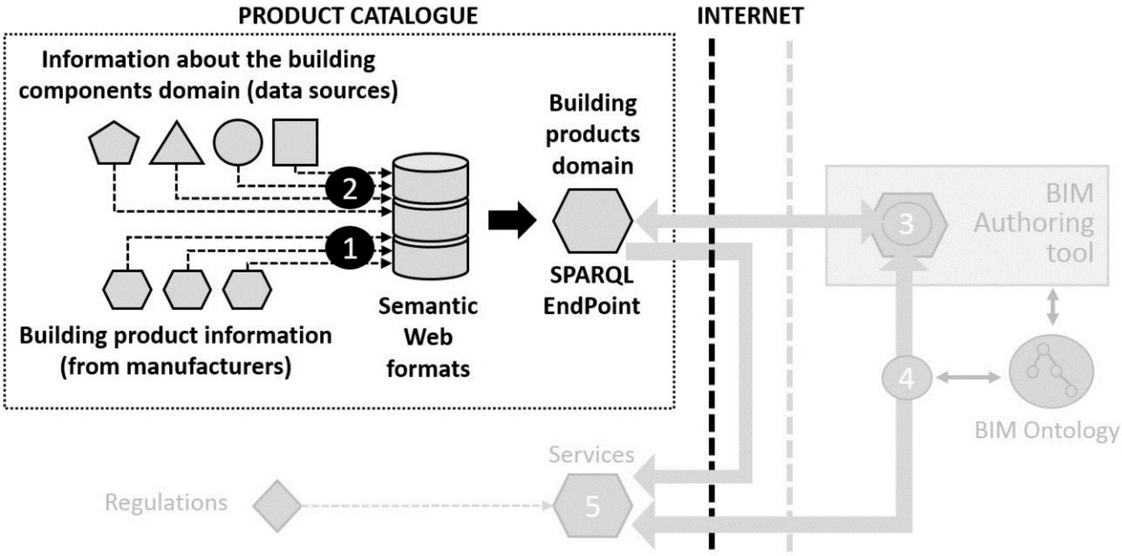


Figure 4.7: Highlighted is the first part of the case study covered in the development of the BAUKOM catalogue.

5

Component checking and product suggestion using Semantic Web technologies

In Chapter 3, methods to facilitate data integration using Semantic Web technologies and linked data were introduced. In Chapter 4, we examined how these methods could be applied to integrate data about building components and products in a catalogue. The implementation of this catalogue was part of a case study by which we addressed the last research question in this thesis: “Can Semantic Web technologies be applied to improve the process of building design and modelling by suggesting to the design team building components and products for a specific project?” The purpose of this chapter is to conclude with a demonstration of the benefits of the use of these technologies within the same case study. To this aim, a method is presented for the creation and usage of semantic inference rules to check BIM models and provide suggestions based on alternative products. The method is applied in a rule-checking and suggestion system that involves three data sources: (1) a BIM model, (2) a catalogue of products, and (3) building regulations. The final part of this chapter is dedicated to describing a prototype service developed as a proof of concept to verify the feasibility of the system for the case of structural components. An example of the application of this service is documented in which hollow-core slab components of a BIM model are checked against a structural safety regulation, particularly the part of the Spanish EHE (Instrucción Española del Hormigón Estructural) regulation that applies to these components (EHE 50.2.2.1). Based on the result of checking, products of the BAUKOM catalogue introduced in Chapter 4 that meet the same requirements are suggested.

5.1. Semantic Web technologies to improve the BIM modelling

This section introduces the context of the last research question addressed in this thesis: “Can Semantic Web technologies be applied to improve the process of building design and modelling by suggesting to the design team building components and products for a specific project?” To address this question, this section starts by examining the problems derived from the inefficiencies in the coordination and exchange of information in BIM-based projects as a result of the involvement of various specialists. Some of these inefficiencies include situations that lead to a redesign. In addressing this problem, we discuss the extent to which Semantic Web technologies can be applied to help building designers to prevent this redesign effort. Among the available tools, we examine the use of semantic inference rules in automated rule-based checking systems. Then, we analyse how these systems can be applied to help building designers to produce models that comply with the calculation requirements and building regulations. The final part of this section describes the barriers and limitations that exist in their implementation.

5.1.1. BIM modelling, calculation and checking applications

As the construction sector is moving towards the adoption of the BIM methodology, interoperability problems are arising mainly between: (1) BIM modelling applications, namely those that allow practitioners to carry out the 3D modelling of the building in different disciplines (architectural, structural, mechanical-electrical-plumbing, etc.), and (2) calculation applications, namely those that enable the experts to adapt the design according to the requirements that need to be met in each of the disciplines involved in a project. One reason for this division is the current lack of capability of BIM modelling applications to address the complexity of calculations performed with specialized applications. However, even when BIM modelling applications can perform some calculations, those corresponding to each discipline in turn require the knowledge and expertise of a specialist. Therefore, the exchange of data between different types of applications is also necessary.

BIM-based projects can be developed using a centralized BIM model or a federated BIM model[94] (Figure 5.1). In both cases, difficulties arise in the coordination among team members and disciplines, requiring continuous evaluations of the design. As it was analysed in Chapter 2, some of the difficulties for this coordination are caused by the lack of mechanisms to properly communicate aspects of the design that cannot be explicitly described. For example, one of these aspects is the design intent, which normally resides in the architect's mind (Abdelmohsen, 2011). Another reason is the lack of information in the hands of designers, which prevents them to foresee or calculate the implications of their decisions. As part of the building design, models of buildings are usually exchanged with various specialists (structural engineers, mechanical engineers, civil engineers, surveyors, etc.) to carry out different types of calculations.

[94] A federated BIM model can be described as "an assembly of distinct models to create a single, complete building information model of an asset" (Paterson, Harty, & Kouider, 2016, p. 259).

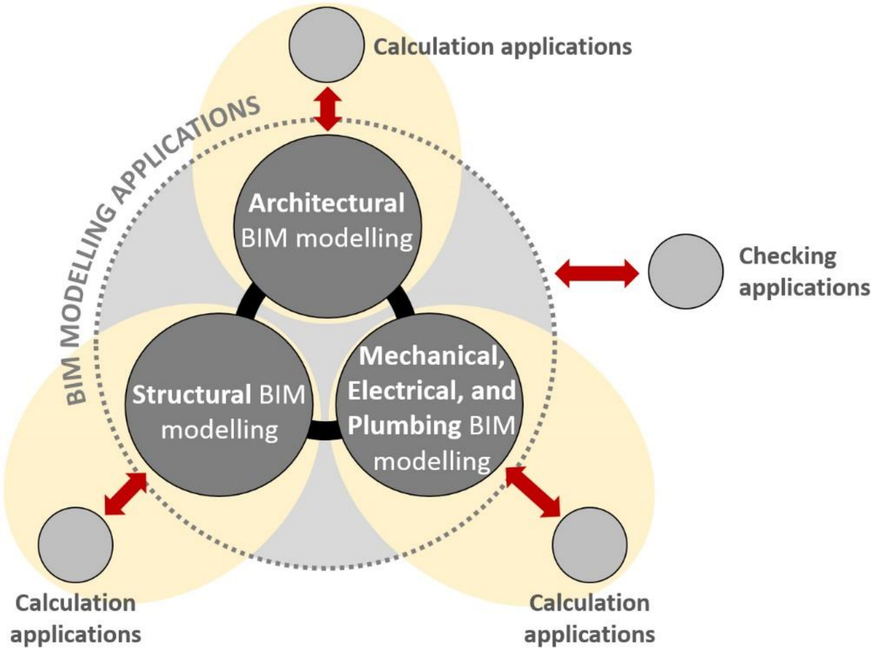


Figure 5.1: Data exchange between BIM modelling, calculation and checking applications in a BIM federated model approach.

The lack of ability to communicate certain aspects of design, as well as the lack of knowledge about the implications of design decisions leads to multiple design iterations. We focus here on the second problem: foreseeing implications of design decisions. In particular, we have investigated how information about some methods implemented in calculation applications can be considered in advance to assist designers to create BIM models. We address the case of models that may not comply with the building codes and regulations applied in calculation tools. This particular case is investigated with an example in which the application of Semantic Web technologies and linked data can be decisive to improve the BIM modelling process.

Building codes and regulations specify requirements that must be met by the project. These need to be considered in each part of the design in which they are applied (energy, acoustics, seismic, structures, fire safety, accessibility, etc.). Their fulfilment is usually the responsibility of a domain expert. For example, a structural engineer must ensure the compliance with structural safety regulations of the building. Typically, regulatory compliance is addressed within the corresponding calculation applications that are used by the experts to produce design solutions which fulfil the requirements of a given domain.

Verifying if a BIM model complies with building codes and regulations may be required specifically during the project. Currently, there are not many software applications which can verify this, despite their increasing need in the development of projects. Moreover, the existing ones only check general requirements (e.g., federated model checking). Most advanced tools enable users to specify building codes and regulations by means of rules. But sometimes, the lack of exhaustive control over the models in relation to the applied rules can lead to errors. For example, a typical case is when the components of the model are not correctly identified. Many times, BIM models are imported into these checking applications through the IFC standard. Here, a poor exportation from the BIM authoring tools may lead to incorrect checking results.

5.1.2. Use of rules and linked data for a more efficient building design

Experts use calculation applications in BIM-based projects to carry out different analysis (structural, mechanical, energy, etc.) of the design. These applications can include the regulations and calculation methods needed to produce valid BIM models according to each discipline. Expertise in performing the calculations is embedded in the applications and in the experts' knowledge. However, some of this knowledge can be represented by common rules and formulas. Moreover, most of the calculations are also based on information (values, limits, coefficients, etc.) extracted from regulations, laws and building codes which are available to the public. This information can vary depending on the geographical scale. For example, public administrations and agencies can define their own regulations, at municipal, regional, national, or international level. Because these regulations are constantly evolving in all legislative domains, flexible, adaptable methods are needed to update them.

Information about formulas, regulations, laws and building codes can be useful to help building designers (e.g., architects) to produce BIM models that satisfy them. Also, this information can help them to create BIM models compatible with specialized tools. Formulas, regulations, laws and building codes can be specified through a set of rules. This way, the rules can be applied to check BIM models through the corresponding functionality implemented in the software applications. However, to achieve valuable results applying these rules, (1) they should be applied automatically in the models and (2) information on corrective actions should be provided when the rules are not satisfied.

Two different approaches can be adopted for the implementation of rule checking methods: declarative and procedural (Pauwels et al., 2011). Currently, most rule checking methods implemented in applications are based on a procedural approach, in which the rules are coded according to the data structures used to represent the BIM models. On the contrary, in a declarative approach, the rules are described separately from the implementation of methods for their application. Advantages of this approach are found in the standardization of the definition and use of rules. Portability and reusability of rules across different applications fits well with the need for methods capable to better suit to the diversity of situations in the development of building projects in which BIM model checking is required.

An important requirement to enable the automated application of rules in the declarative approach is the compatibility between the languages used to describe the rules and BIM models. In Chapter 2, we indicated that the IFC standard provides a basis for representing BIM models using a common language and semantics. However, the SPF and XMLversions of IFC do not have any formal logical basis and are hence not compatible with the targeted logic-based rule languages. As an alternative, a standardized and compatible basis of logic-based description languages to define BIM models and rules can be found in the Semantic Web domain. In Chapter 3, we saw that there are various languages in the domain of Semantic Web designed to describe rules. Using these languages, formulas and mathematical calculations can be described as formal logical statements. However, to combine them with BIM models, these latter must also be described in logic-based languages. In Chapter 3 we also saw that the RDF and OWL languages can be used to describe BIM models, thus providing an opportunity to combine building information with formal rules.

Rules can be combined with plenty of other data that is available in the same format (RDF). This includes the building component data in the BAUKOM catalogue, but also data related to building codes and regulations like coefficients and values that can be subject to changes. BIM data or other data provided in these data sources need to be represented according to a known data schema (ontology) if we want to be able to use them on a large scale.

The use of linked data in software services can be facilitated through the processing of rules, but also indirectly with the implementation of services. This may occur when information related to a domain can be useful to inform and guide designers about possible actions to be carried out in the BIM model. For example, when a rule applied in a BIM model shows that one or more aspects of a regulation are not fulfilled, corrective actions can be suggested. Services designed for this purpose can be implemented as applications on the Web and plug-ins developed for BIM applications. A case in which this type of service may be useful is pre-dimensioning of structural components. The context of this case is introduced and discussed in more detail in the following sections of this chapter.

Figure 5.2 shows the relation between software services using rule sets implementing checking/calculation methods and data linked to different sources. The services enable building designers to create BIM models which are compliant with the building codes and regulations, and closer to the design solutions to be calculated in specialized tools.

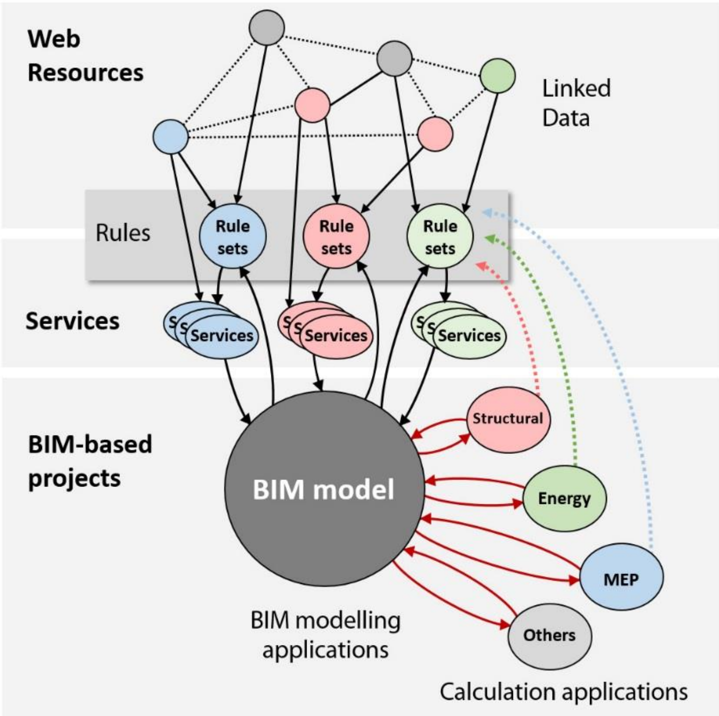


Figure 5.2: Relation between software services using rule sets implementing checking/calculation methods and data linked to different sources.

The application of Semantic Web technologies is not specific to the AEC sector. The reuse of rules and data to facilitate more dynamic and adapted implementations through the application of Semantic Web technologies has also been investigated by many other industries. As introduced in Section 3.2.2, currently there is an increasing number of data sets described according to the principles of linked data. Many of them are published as Linked Open Data (LOD) on the Web. This way, through their publication, services and applications can be developed taking advantage of the data defined as LOD, for example, to carry out reasoning and rule-checking processes over distributed datasets.

5.1.3. Automated rule-based checking

The use of rules to check BIM models has become very useful and necessary to validate the solution of building designs according to different criteria and analysis. The clearest example can be found in checking regulations and building codes. Today, building construction is increasingly subject to checking the compliance of building codes regarding, for example, spatial systems, structural integrity and safety, costs, and energy usage. The checking and evaluation of building code requirements is a promising area for BIM applications and services (Eastman et al., 2011; Zhang, Teizer, Lee, Eastman, & Venugopal, 2013). Mechanisms for automated or semi-automated rule-based checking are demanded by architects and engineers in order to avoid wasting time in manually checking the building designs (Wix, 2008).

Within the AEC industry, automated rule-based checking refers to a software capability to check and evaluate BIM models through a set of defined rules. The implementation of these rules relies on how the components of a BIM model are parameterized and configured. Outputs obtained from the application of rule-based checking processes in a building design can be classified as “pass”, “fail”, “warning” or “unknown”, depending on the type of checking required (Eastman et al., 2009).

Automated rule-based checking has been investigated for years as a way to replace the manual checking of regulatory compliance in building projects. For example, Ding, Drogemuller, Rosenman, Marchant, and Gero (2006) proposed DesignCheck, an automated code checking system for compliance with building codes on the fly at various stages (early design, project design and specification). In this system, BIM models exported from CAD vendors in IFC2x2 are mapped to an internal model. Moreover, building codes are represented as object-based interpretations to facilitate their encoding into Express Data Manager rule bases. Object-based interpretation facilitates the definition of building codes with “elements”, “properties”, “relationships” and “domain-specific knowledge for interpretation”. Compliance checking is then achieved by processing the rules embedded in the object-based interpretation, corresponding to each building code clause, against the internal model.

Performing manual checking operations is often a cumbersome, costly and error-prone process (Gallaher, O’Conor, Dettbarn, & Gilday, 2004; Preidela & Borrmanna, 2015; Zhang & El-Gohary, 2012; and others). As the AEC industry is embracing the BIM methodology, it should be easier to carry out automatic checking (e.g., check the minimum dimensions that must have the hallways and doors of a building to comply with accessibility requirements provided in the corresponding regulation). In BIM-based projects, stakeholders share virtual models of the building, which are created through the assembly of 3D parametric components. These components are geometrically defined through a parametrization that can be inferred. This way, checking mechanisms can be used to evaluate the models based on the configuration of the components, the attributes included in them and their interrelationships (Nawari & Alsaffar, 2015). Components can include values, coefficients, and formulas that can be processed to facilitate some of the checking processes. For example, the “thermal mass”[95] property and its value must be included in the information of components if we need to perform a thermal simulation of the building.

A correct specification and classification of the components of a BIM model is important to be successful in rule-based checking processes. For example, an object that looks like an I-type beam in a BIM model, but which has not been created using the corresponding native class, will be invisible to the rules that apply to this type of component. BIM authoring tools usually provide a specific behaviour for each type of component in order to facilitate proper assembly. For example, walls cannot be connected to foundations. Conversely, walls can be connected to two columns, and if they change their position, the wall is automatically resized. A proper description of the relationships between components is also required for rule-based checking processes.

[95] In building design, the “thermal mass” refers to the ability of materials to store heat energy.

There are cases in which the application of automated rule-based checking processes to a BIM model may be more appropriate than others. Eastman et al. (2009) define three cases: (1) when rules can be defined and applied independently to any building modelling system; (2) when administrations, agencies and clients need to check designs created through an open-ended set of design tools; and (3) to check general conditions (e.g., rules associated with safety regulations).

5.1.4. Barriers and limitations

Automated rule-based checking systems can be implemented, for example, in stand-alone desktop applications, in plug-ins developed for specific BIM platforms or as web services on the Web (Eastman et al., 2009). In most cases, the checking rules are hard-coded in algorithms. However, they are limited in the capacity to process complex design parameters, so the knowledge of the experts is still required (Zhang et al., 2013). Although some BIM checking applications (e.g., Solibri Model Checker) enable users to define rules to check the model, most of these applications are very limited in providing mechanisms to define new types of rules apart from those already provided in the application.

A common feature of rule-based checking systems is that they do not usually modify the information of the BIM model (Eastman et al., 2009). This means that if a model does not pass the checking, designers have to modify the design and check it again. Furthermore, BIM models are generally checked for domains and disciplines for which they have been created, without considering the requirements from the others. This means, for example, that a model created by a member of the design team, which has been checked and validated according to his discipline, may fail when it is checked according to the requirements of another discipline, requiring to carry out a redesign.

An important part of the research in automated rule-checking systems conducted in recent decades has been aimed at describing the information about building codes and regulations in a machine-readable form (Eastman et al., 2009). However, finding an efficient and practical representation of a set of regulations in a set of processable rules still remains a challenge today (Dimyadi & Amor, 2013). This is mainly because a significant part of the regulations is described in human language and usually provided in text documents. Moreover, there is a part that often remains subject to the interpretation of an expert, since some of them can be interpreted in more than one manner. For example, sometimes regulations are described using vague terms, such as “close to” or “easily accessible”, and expressions that are difficult to verify when they are not logical propositions (Martins, Carvalho, & Almeida, 2016).

Several researchers have attempted to create procedures to extract information from regulatory documents in order to provide computable specifications. One of the most widely used methods to extract this information is to apply natural language processing (NLP) techniques such as entity recognition, sentence splitting, tokenization, tagging and syntactic parsing. Checking methods based on these techniques can be found in some recent research works, for example in Zhang and El-Gohary (2012) and Nawari and Alsaffar (2015).

However, there are a number of factors that make it difficult to extract rules from regulations: they are often incomplete; they come into conflict with each other, or they even become incompatible with the new reality of the AEC industry as it evolves. A typical example is the mismatch between regulations that are defined at national and regional level.

Current checking systems are mainly based on rules embedded in software applications which cannot be modified by users. Furthermore, to be truly effective, these rule-based checking systems must suggest corrective actions. Such suggestions can be provided as new information to be added to the BIM model which then is modified by the designers. In a semantic context, rule-based checking systems could be implemented as services that may be invoked from BIM applications. To the extent that the BIM data can be represented with Semantic Web standards, it would be possible to carry out their checking through semantic rule-checking processes, taking advantage of the logical underpinning of languages like RDF (Pauwels & Zhang, 2015), as well as the benefits of the linked data.

5.2. Automated rule checking based on linked data principles

The formal semantics included in semantic web languages constitutes a reliable basis for reasoning, since they are based on first-order logic (Klyne & Carroll, 2004). One of the benefits in using these rule languages lies in their ability to create rules that can be shared and reused (Rattanasawad et al., 2013).

5.2.1. Semantic inference rules

An explicit representation of the knowledge provided through the Semantic Web languages (RDF, RDFS and OWL) enables deductive and automated reasoning applying semantic inference rules. These rules can be created as IF-THEN statements in RDF. The application of these rules enables new knowledge to be inferred, also in the form of RDF statements. As such, semantic inference rules provide a mechanism for extending knowledge represented in an RDF graph (described in the IF part of the rule) with new knowledge that can be logically inferred (described in the THEN part of the rule). The IF part of these rules includes a pattern defined as an RDF graph corresponding with the part of the model to be processed by the rule. In addition, this part can include the conditions and constraints that need to be met through logical functions and operations. This way, every definition in the model that matches the RDF graph pattern will be processed according to these conditions and constraints. If they are met, new facts can be inferred since THEN parts of the rules capture the conclusions that need to be drawn accordingly. Therefore, a BIM model described as an RDF graph can be extended with additional information. For example, it can be inferred that some regulations are not met for some components.

Figure 5.3 shows an example of a simple inference rule used for pre-processing information about a BIM model. The rule looks for slab components with a standard width, in this case equal to 1200 millimetres. For each case in which the condition of the rule is met, the statement "Has standard width" is inferred and added to the model as a new property (as an informative note) of the component.

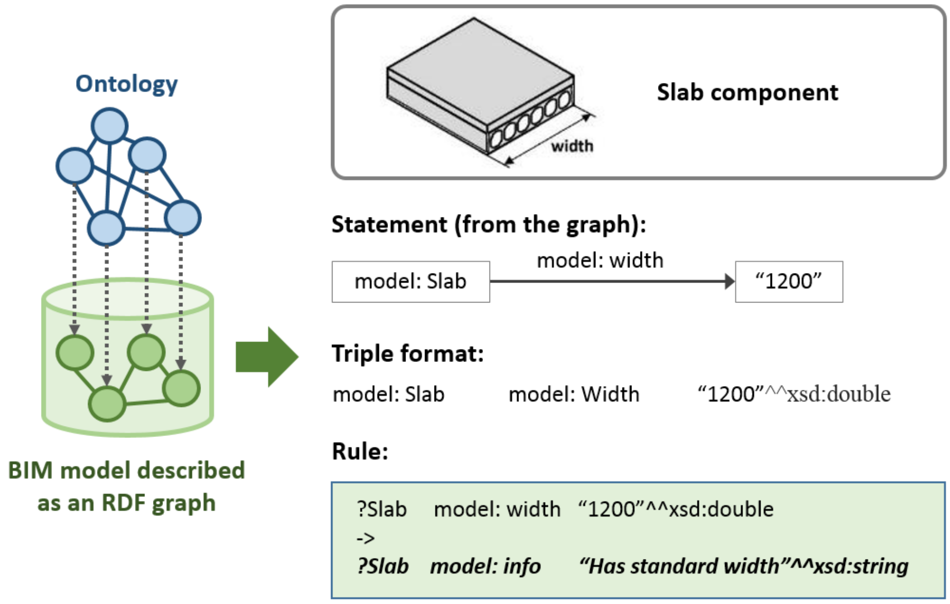


Figure 5.3: Example of a simple inference rule used for pre-processing information about a BIM model.

As stated in Costa and Pauwels (2015), two conditions are required to be able to create and apply semantic inference rules for BIM models. First, in order to create the IF part of the rule, one must know the data structure of the RDF graph in which the information of the BIM model is represented. The RDF graph can be extracted from the ontology used to describe the model. For example, BIM models described in the IFC standard can be transformed into RDF data according to the ifcOWL ontology. Second, the modelled part of the building that needs to be checked by the rule must include the information necessary for its evaluation. That is, if the data corresponding to the pattern to be checked are incomplete, the rule cannot be applied.

As introduced in Section 3.2.3, semantic inference rules are processed by inference engines (also known as reasoners), which search for patterns embedded in the IF parts of the rules that match with the data provided in the RDF model, in this case representing the information of a building model.

5.2.2. Review of semantic rule-checking approaches

Several research works have been carried out in recent years in which rule languages have been applied to check BIM models described in the Semantic Web formats. For example, Pauwels et al. (2011) devised a semantic rule-based system for checking building performance. This system was applied in a test case to check the compliance of the acoustic regulation in BIM models. For this purpose, semantic inference rules described in N3Logic language were implemented to check instances of building models described according to a domain ontology. In particular, a rule set was defined to verify two standards based on acoustic regulations defined at national (Belgium) and European level:

(1) NBN S 01-400-1:2008[96] and (2) EN 12354-3:2000[97]. The use of two standards was justified because the European regulation only provides a formula to derive the required quantities while the process for their evaluation is described in the national regulations. They used the EYE reasoning engine (De Roo, 2012) to process the rules in order to verify whether or not a building design complies with the regulations.

Figure 5.4 shows the two formulas used to calculate the sound power ratio in façade elements according to the European standard EN 20140-10 (top of the Figure 5.4). The second formula is translated into one of the regulations of this standard for the acoustic isolation of airborne sound against outdoor sound (EN 12354-3:2000). The corresponding code is embedded in an inference rule to derive the "directSoundPowerRatio_4000Hz" property, against building models (bottom part of the Figure 5.4) (Pauwels et al., 2011).

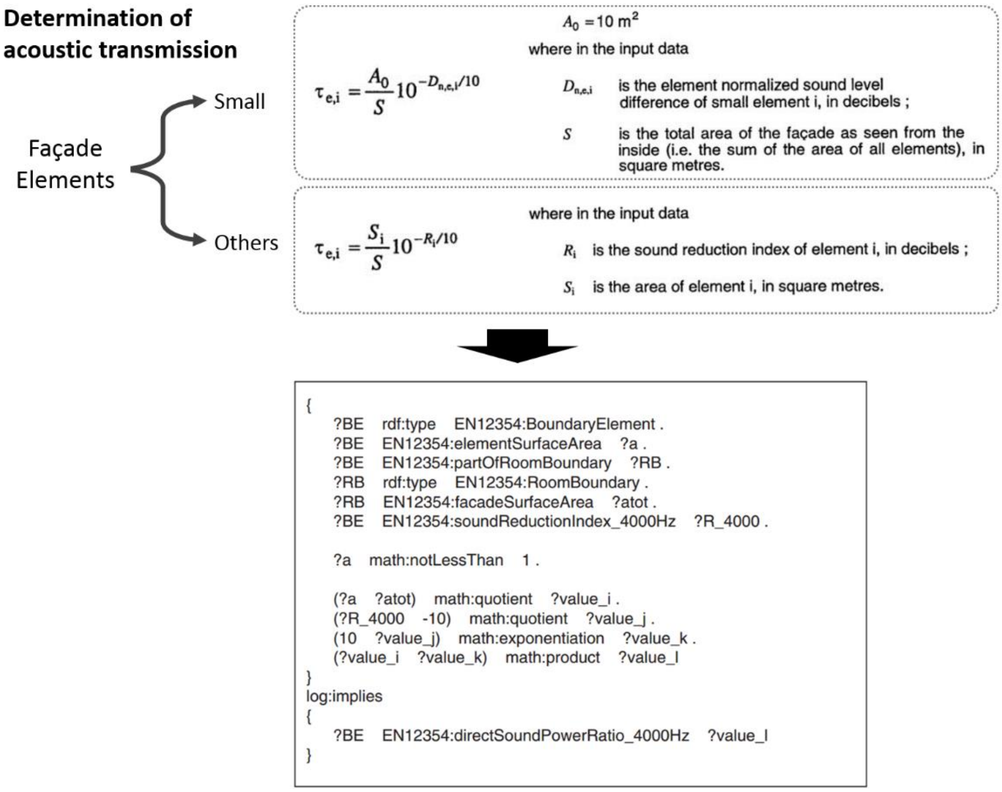


Figure 5.4: Inference rule to calculate the sound power ratio in façade elements (Pauwels et al., 2011).

[96] Bureau voor normalisatie – Commissie: Geluidsleer – algemeen, Belgische norm NBN S 01-400-1, Akoestische criteria voor woongebouwen – Critères acoustiques pour les immeubles d'habitation (2008). Retrieved from http://www.nbn.be/en/buying-standards/individual-standards/.

[97] European Committee for Standardization (CEN), European Standard EN 12354-3, Building Acoustics – Estimation of Acoustic Performance of Buildings from the Performance of Elements – Part 3: Airborne Sound Insulation Against Outdoor Sound (2000). Retrieved from https://www.iso.org/obp/ui/#iso:std:iso:15712:-3:ed-1:v1:en.

Another example where semantic rule languages have been applied can be found in Farias et al. (2014) (Farias et al., 2014). They developed an ontology as a subset of the IFC standard. They also implemented a set of SWRL rules at the top of this ontology which described the business needs of an end-user (client). With the combination of ontology and rules, they separate the meaning of the concepts of the BIM model from their semantics defined in the IFC files. This way, it is possible to increase the expressiveness of BIM models without affecting their interoperability with the IFC. To carry out this process, they created an automatic parser to generate an IFC ontology from an EXPRESS version following a process inspired by the model proposed by Beetz et al. (2009). Next, they created the SWRL rules at the top of the ontology using an ontology editor. Finally, the ontology and rules were uploaded into the Stardog RDF database, a triple store that supports reasoning over the SWRL rules. They also developed another parser to extract specific data from BIM models provided in IFC. The parser generates the respective concept instances. This way, the data are automatically restructured according to previously defined SWRL rules, but maintaining the interoperability with the original IFC models (Farias et al., 2014).

Other research works on the use of semantic rule languages in the area of BIM can be found in Choi and Kim (2016), Li (2015), Smart (2007), and Solihin and Eastman (2015).

5.3. Checking BIM models and making suggestions for these models regarding building component products

The second part addressed in this chapter investigates the application of semantic inference rules to check the building components of a BIM model and to provide suggestions based on alternative products when possible. One of the key decisions in building projects is the choice of products and materials. As concluded in Chapter 4, more comprehensive product information is required by building designers to find the most suitable materials and components for a project (e.g., related to their availability or compliance criteria). This section starts by analysing the information which is required to choose building products.

The ability to check the suitability of a building component or product according to a number of evaluable conditions can be combined with the proposal of alternative components and products which satisfy the same conditions. With this purpose, we propose a method for the creation and usage of semantic inference rules. The method is applied in a rule-checking and suggestion system where semantic inference rules are the core of the system. The second part of this section introduces the characteristics and the method developed for the creation and usage of semantic inference rules.

5.3.1. Requirements and needs

This section analyses the main needs of architects and building designers in the process of taking decisions about products and components for BIM modelling. As it was introduced in Chapter 1 (Section 1.2), there are different requirements for the choice of components and products depending on the agent, discipline and the stage of the building life cycle.

These needs were classified according to:

- Availability. When architects, designers and owners, mainly, decide to opt for components and products to create their designs and building models, whether in the early or advanced stages of the project, sometimes these products do not exist on the market; they cannot be produced by any manufacturer; the cost is too high to make them viable in the project; or products provided by the manufacturers may not be available when they are needed.
- Compliance criteria. When architects, designers and owners wish to check that products meet with the current regulations, under different criteria and with restrictions imposed by owners and builders. Furthermore, they wish to simplify some parts of the process (e.g., pre-dimensioning of the building components of the model to simplify the process of structural design), and prevent incompatibility between components.

As stated in Costa and Pauwels (2015), having information about building products can be useful to check if:

- It is easily available in the area of the future construction site.
- It is within the budget of the project.
- It complies with project requirements.
- It conforms to the European, national and local regulations.

In light of the needs and reasons why this support is required, a rule-checking and suggestion system was devised based on checking building components of BIM models (Costa & Pauwels, 2015). In this system, semantic inference rules were created to link data from product catalogues and regulations provided on the Web described in Semantic Web formats (RDF, RDFS and OWL). By using these rules for checking BIM models, suggestions can be provided to the design team members on the most suitable building components and products for them. This system is described below.

5.3.2. Rule-checking and suggestion system

A method was developed for the creation and usage of semantic inference rules for checking BIM models and suggesting building products as valid candidates (Costa & Pauwels, 2015). This method was applied in a rule-checking and suggestion system that involves three data sources: (1) a BIM model, (2) a catalogue of products, and (3) building regulations. The system includes different components connected to provide this support (Figure 5.5).

The method consists of three steps. First, an ad hoc ontology to represent BIM models according to the data structure of a BIM authoring tool is created (left in Figure 5.5). Based on this ontology, the information about the BIM model can be represented in RDF (point 1 in Figure 5.5). This export can be performed, for example, through a plug-in. It is important to note that to create semantic inference rules to check BIM models, the corresponding ontology that defines the information of the model needs to be available. In this case, the option of providing ontologies for each BIM authoring tool has been considered as an alternative approach to solutions based on ifcOWL for two reasons: (1) the complexity associated in the multiple ways to represent building designs in IFC and (2) the limited number of BIM authoring tools currently in the market that are used by the majority of the industry. This last reason led us to think that the use of ontologies to describe the data models implemented in BIM authoring tools could be considered as a feasible and reasonable alternative to facilitate the checking. Currently, the representation of BIM models in IFC which could be verified without ambiguity still requires more research work by the community.

To link the information about the other two data sources (product catalogues and regulations) different options can be considered. This information can be provided as files available on the Web and accessible through a dereferenceable URI or through some kind of service (e.g., through a SPARQL endpoint). An example of how information about building components and products can be facilitated in the Semantic Web formats through the Web is the BAUKOM catalogue (point 2 in Figure 5.5). Unlike regulations, product information is not included in inference rules but retrieved from the catalogue through a SPARQL query including the parameters that are required for the checking. This process is explained in more detail in the demonstration case.

For the building regulations, a process is necessary to extract the information from the documents where they have been described (point 3 in Figure 5.5). This should be a task to be performed in the future by the public administrations, since they are responsible for this information. For the demonstration case, the information about the safety calculation in concrete structures is manually extracted from official documents. The aspects related to this regulation and the rules extracted from it are introduced in Section 5.4.3.

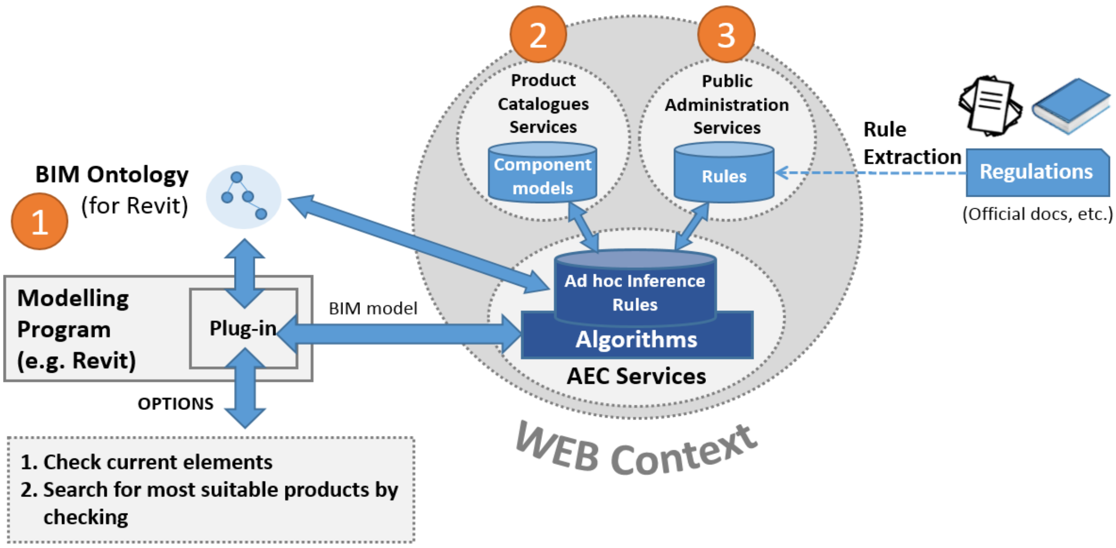


Figure 5.5: Diagram showing the connection between the three components of the Rule-Checking and Suggestion System (Costa & Pauwels, 2015).

With the combination of these three data sources (1, 2 and 3 in Figure 5.5), inference rules can be processed to enrich BIM models with additional information for a particular type of check or suggestion.

5.4. USE CASE: A service to check hollow-core slabs in BIM models and suggest products based on these components

With regard to the rule-checking and suggestion system introduced in the last section, a particular use case based on this system was implemented in a service in (Costa & Pauwels, 2015) to demonstrate its feasibility. This use case was defined for the context of structural modelling (Figure 5.6).

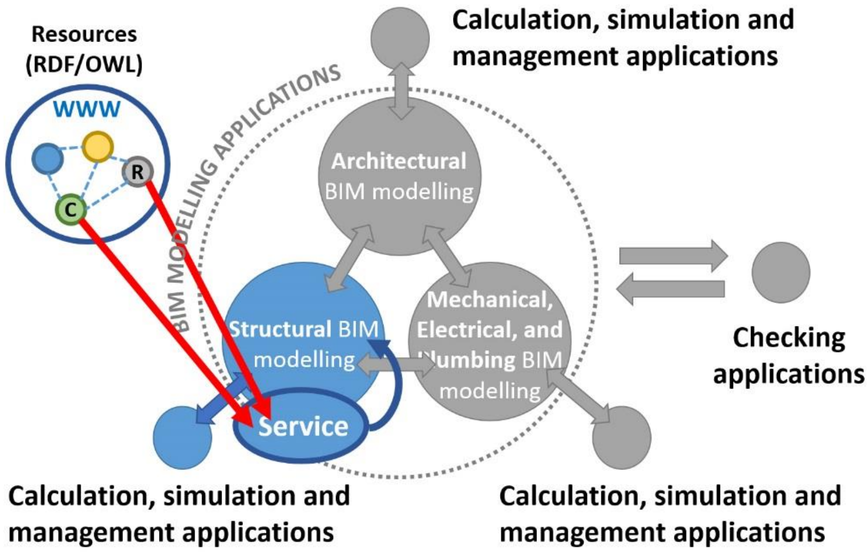


Figure 5.6: combination of information from Web resources in services to assist in structural BIM modelling.

5.4.1. Structural modelling

Buildings constructed with precast concrete components have associated specific characteristics that must be taken into account in building design. For example, one of the design objectives when performing the structural modelling is to create the most slender structure possible to minimize the amount of concrete, which has a direct impact on the cost of the project.

Each of the components that make a structural system has a different function, which determines the order in which it can be connected with the others. The components that are subject to forces transmitted through others (e.g., columns which are usually subjected to combined compression and simultaneous axial and lateral forces) require complex formulas and methods to calculate the appropriate dimensioning. However, this calculation is often less complex for components that do not bear loads from other components (e.g., slabs and hollow-core slabs). In any case, all of them need to comply with the structural integrity and with the corresponding building regulations.

Typically, structural engineers are responsible for the structural calculations, but the overall design of the building is mainly the responsibility of the architects. This division of tasks leads to carrying out several iterations to find the solutions that fulfil all requirements from architectural and engineering standpoints. Typically, structural design starts with re-dimensioning the components that make the structure and then moves on with a detailed structural analysis. It is at this pre-dimensioning stage when the dialogue between architects and structural engineers starts. An accurate pre-dimensioning of the building structure can reduce the iteration process and facilitate the interaction between both experts at this early stage of the design.

To help architects to create models with an accurate pre-dimensioning of precast structural components, a rule-checking and suggestion system was devised (see Section 5.3.2). The feasibility of the service was demonstrated in the calculation of hollow core slab components. The service automatically checks the components of a modelled part of a building structure against the structural safety regulations applicable to this type of components. Formulas extracted from the regulation are encoded in the inference rules and calculated using the values of basic parameters defined in each (dummy) hollow core slab component of the BIM model. Based on the result of the checking, the service suggests valid hollow core slab products that may be used in the structure of the building. Products for this type of component are obtained by querying the BAUKOM catalogue (via SPARQL queries). Products that satisfy the values calculated in the inference rule are added in the BIM model in form of new RDF statements.

Support for this pre-dimensioning is illustrated in a very simple example shown in Figure 5.7. In the example, a model of a simple building structure which includes a set of hollow core slab dummy components, translated to RDF, is processed by the service through an inference rule. In this case, the rule enables to check the components according to section 50.2.2.1 of EHE regulation, and based on the result, the service suggests the most appropriate hollow-core slabs products retrieved from the catalogue. This information is included in the model in the form of new RDF statements.

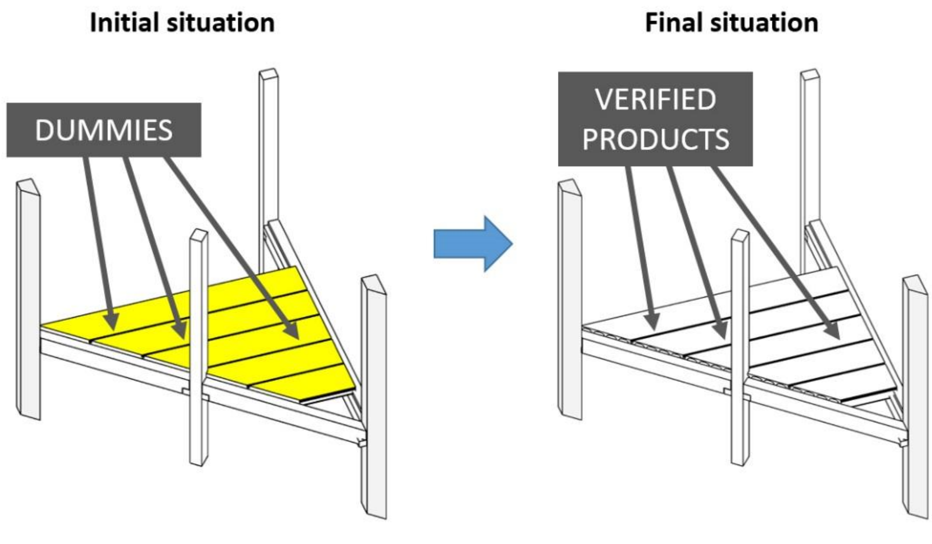


Figure 5.7: Example showing the pre-dimensioning of hollow-core slabs components using the prototype service implemented.

5.4.2. Data sources

The following three data sources were considered for the service:

1. **Revit**. A BIM model extracted from the Revit tool (data).

2. **BAUKOM catalogue**. Building product data retrieved from the catalogue (data).
3. **EHE 50.2.2.1**. A formula implemented in the inference rule (rule).

As a proof of concept for the demonstration of the service, a representative data set was extracted from a BIM model created in Revit. A simple ontology was created to represent this model. Figure 5.8 shows the most relevant part of this ontology and the corresponding RDF graph representing the instances of the components of the model. The part of the ontology represented in this figure shows five related OWL classes, which represent the five types of structural components that make up the model.

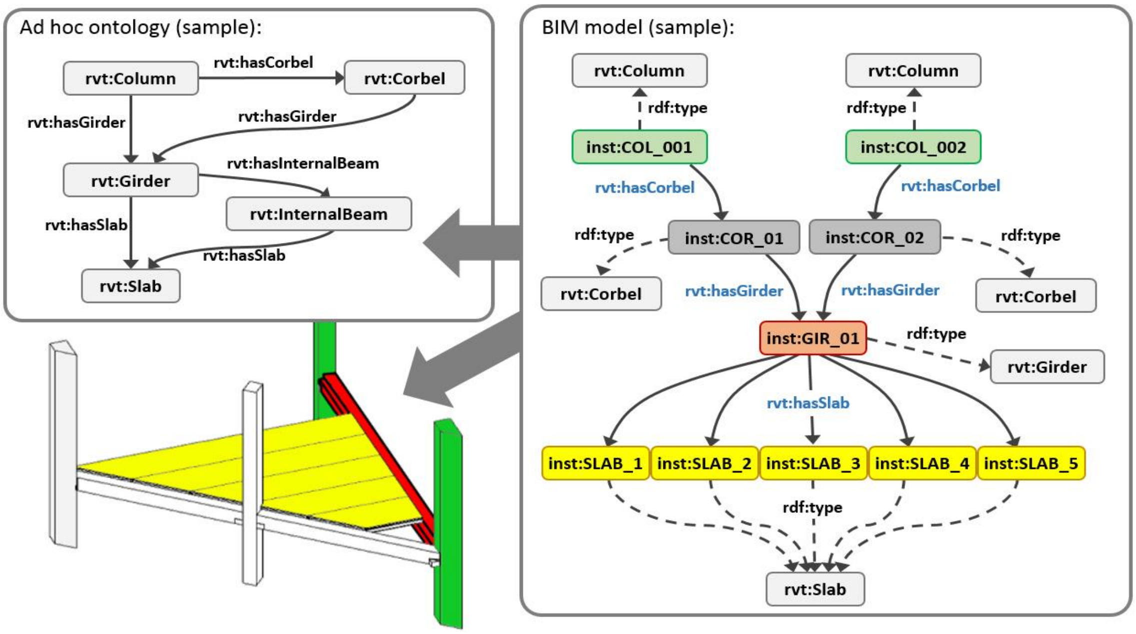


Figure 5.8: Most relevant part of the ontology and its instantiation for the proposed example as an RDF graph.

The second data source used in the service developed is the BAUKOM catalogue. Since information about this catalogue is provided through a SPARQL endpoint, SPARQL queries were created to retrieve the necessary information about the products. As in the case of a BIM model, product information is provided in RDF. As for the EHE regulation, the third data source, a formula that validates the safety conditions for the case of hollow core slab components (50.2.2.1) was extracted and encoded in an inference rule. Another rule was created to evaluate if the components could be checked with this formula. The following section introduces the EHE regulation, the part related to the hollow core slab components, and the process followed to transform the formula provided in the official document into an inference rule.

5.4.3. Safety calculation in concrete structures

The Spanish safety regulations for concrete structures, EHE was chosen to check the structural components of BIM models. In particular, the formula corresponding to the safety calculation on hollow-core slabs (EHE 50.2.2.1) was extracted. This formula can be used to estimate the minimum height of the slabs which approximates the complex flexural strength calculation (Figure 5.9). This formula can be applied when two basic conditions are met: (1) the distance between the two columns is equal to or less than 12 metres and (2) its overload must be less than 4 kN/m^2. In addition, the formula is applicable as long as the hollow-core slabs do not exceed their flexural cracking, as a consequence of an infrequent combination of loads.

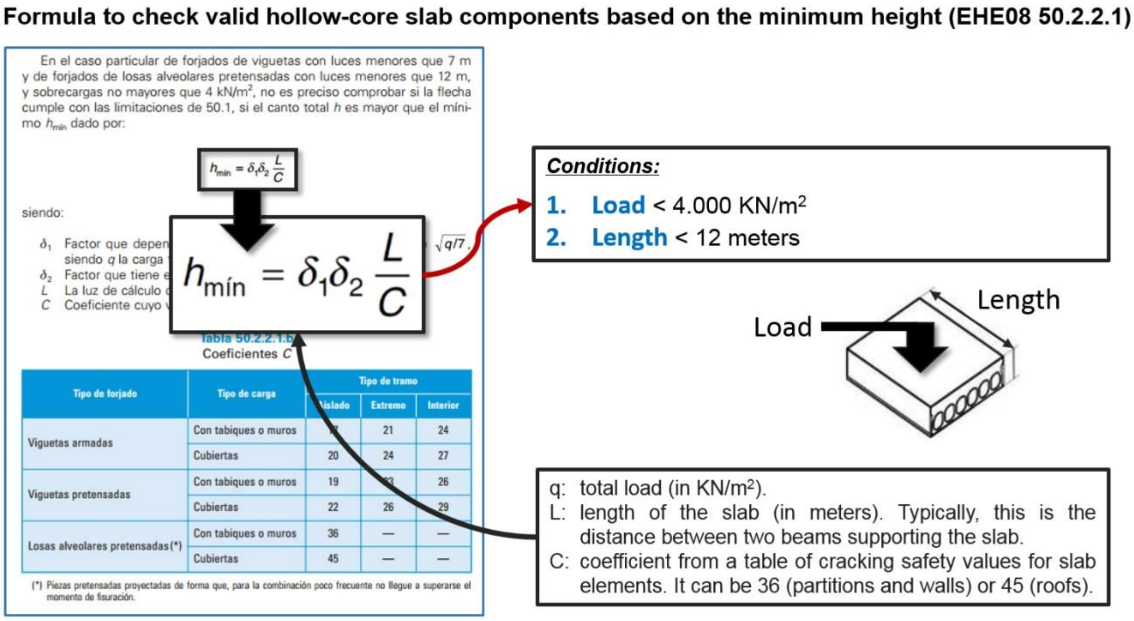


Figure 5.9: Spanish regulation for the structural safety that applies to hollow-core slab components (EHE08 50.2.2.1).

An inference rule was implemented to identify whether hollow-core slab components satisfy the two conditions necessary to apply the formula (Figure 5.10). This way, when a component fulfils the two conditions, this information is added into the RDF graph indicating that the component can be assessed with this method. This is a necessary step to infer the appropriate calculation method to be applied in a next step.

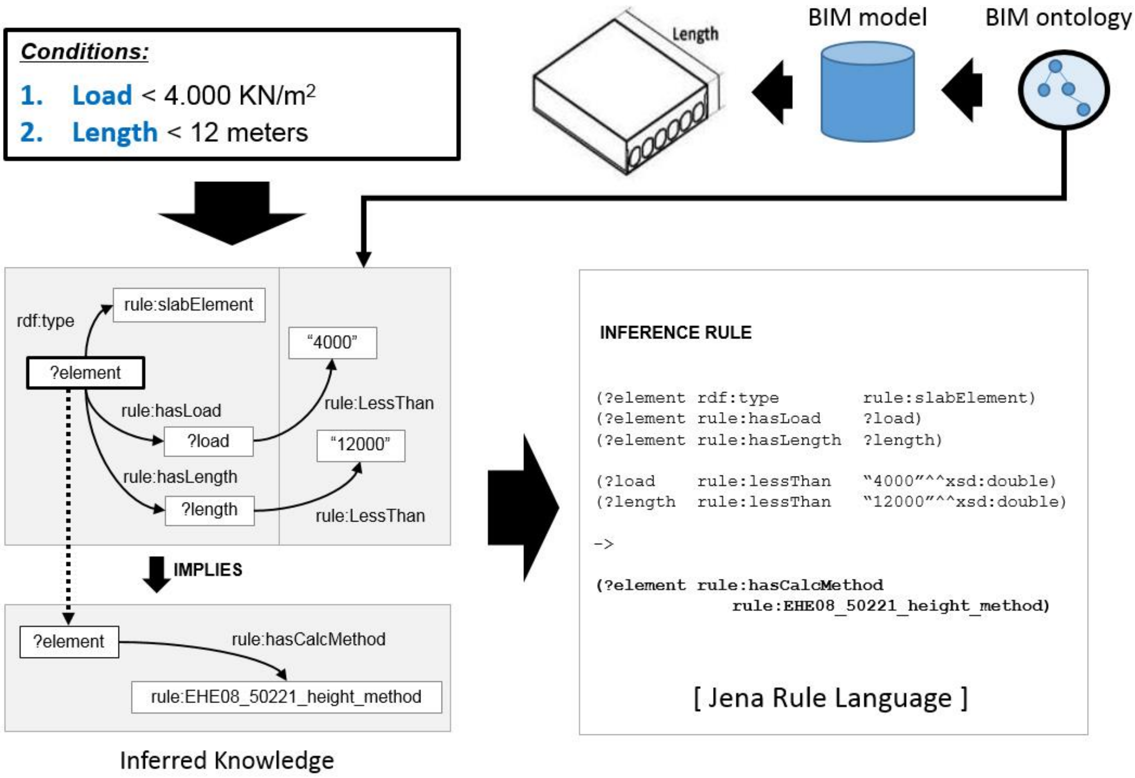


Figure 5.10: Inference rule designed to infer whether a hollow-core slab can be evaluated by the formula provided in the regulation EHE08 50.2.2.1.

5.4.4. Rule-checking process and suggestion

Based on the three data sources described above as inputs for the rule-checking and suggestion system implemented in the service, different rules can be created for their further processing (Figure 5.11). These rules are defined in the Jena Rule language and are processed using Apache Jena, a Semantic Web framework for Java whose syntax is based in RDF. The framework includes reasoning engines capable of processing these rules.

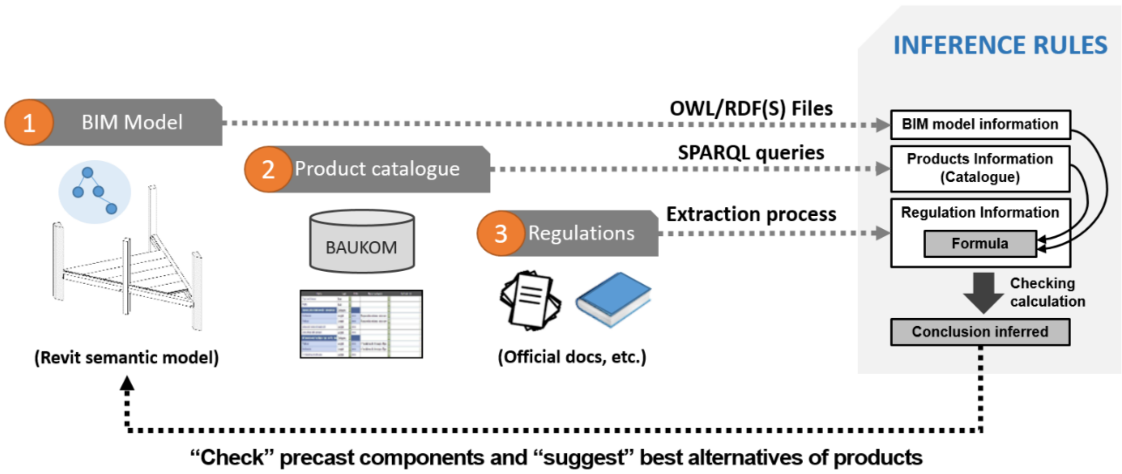


Figure 5.11: Diagram showing the data sources that are required for the creation of inference rules.

As a proof of concept, an inference rule has been created to calculate the minimum height of hollow-core slab components defined in a BIM model, including the formula defined in the regulation EHE 50.2.2.1. The following explains in detail the composition of the inference rule which is divided in three parts. The first part includes the data of the BIM model to be processed, in this case the corresponding RDF graph definition of a hollow-core slab component (Figure 5.12). All the properties and concepts defined in the graph must be instantiated for all the hollow-core slab components ("rvt:slabElement") included in the BIM model to be processed.

```
PART 1: DATA REQUIRED FROM THE BIM MODEL
@prefix rvt: http://www.autodesk.com/revit/ontology/revit2015#
@prefix cte_EHE08:
http://www.codigotecnico.org/cte/export/sites/default/web/galerias/archivos/DB SE-
AE abril 2009
@prefix rule: http://internal.rule.values#
[rule:
        (?slabDummy rdf:type rvt:HCSlabElement)
        (?slabDummy rvt:variableLoad ?variableLoad)
        (?slabDummy rvt:length ?length)
        (?slabDummy rvt:width ?width)
        (?slabDummy rvt:height ?height)
        (?slabDummy rvt:weight ?weight)
        (?slabDummy rvt:compressionLayerHeight ?compressionLayerHeight)
```

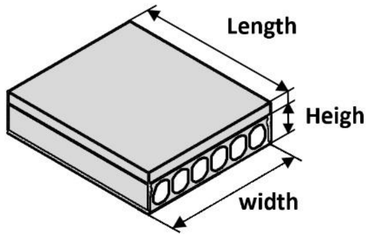


Figure 5.12: Part of the inference rule corresponding to the information about the RDF graph of the BIM model (PART 1).

The second part includes the codification of the formula defined in the EHE 50.2.2.1 regulation. Figure 5.13 shows the code of the rule which is used to infer whether the calculated value satisfies the condition of minimum height for each hollow-core slab component of the BIM model to check.

This stage includes a series of steps. The instances of the hollow-core slab component of the BIM model are represented by the "?slabDummy" variable in the code. The value of various parameters of these components is necessary for the processing of the formula: (1) maximum variable load, (2) length, (3) width, (4) height, (5) weight and (6) the height of the compression layer. Having processed the formula, the calculated value will remain in the "?minimumHeightBorderValue" variable. In the next step, this value is compared with the "?height" variable (the current height of the component). Finally, the result of the subtraction of the two values will be contained in the "slabHeightDifferenceValue" variable (in bold). In the last step, the value of this variable is compared with zero. This way, if the value is less than zero the condition will be validated, which means that the regulation is fulfilled.

PART 2: BUILTIN OPERATIONS TO CALCULATE THE FORMULA.

```
product(?compressionLayerHeight "2.5"^^xsd:double ?CompressionVariableLoad1)
product(?CompressionVariableLoad1 "9.8"^^xsd:double ?CompressionVariableLoad)
sum(?variableLoad ?CompressionVariableLoad ?totalLoad_q1)
sum(?totalLoad_q1 ?weight ?totalLoad_q)
quotient(?totalLoad_q "7"^^xsd:double ?SqrtValue)
sqrt(?SqrtValue ?HCS_Value_Sqrt)
quotient(?length "6"^^xsd:double ?HCS_Lenght_Div)
pow(?HCS_Lenght_Div "0.25"^^xsd:double ?HCS_Lenght_Pow)
quotient(?length "36.0"^^xsd:double ?HCS_Lenght_Height_Div)
product(?HCS_Value_Sqrt ?HCS_Lenght_Pow ?prod1)
product(?prod1 ?HCS_Lenght_Height_Div ?prod2)
difference(?prod2 ?compressionLayerHeight ?minimumHeightBorderValue)
difference(?minimumHeightBorderValue ?height ?slabHeightDifferenceValue)
lessThan(?slabHeightDifferenceValue "0.0"^^xsd:double)
```

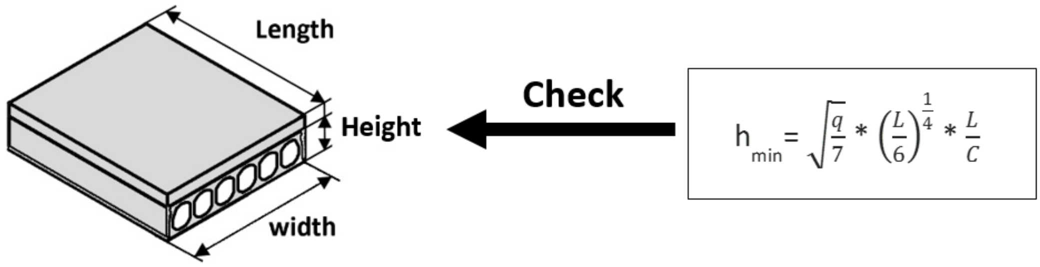


Figure 5.13: Part of the rule describing the calculation process according to the EHE 50.2.2.1 formula (PART 2).

The third part of the rule includes the information that will be added into the RDF graph of the BIM model if the condition is validated. This information should help designers to identify the invalid components of the model in accordance with the regulation.

It is important to note that two versions of the rule are necessary to check if the regulation is satisfied or not, one for each case. This is because the reasoning through semantic inference rules is subject to the open world assumption (OWA), where any statement – in this case, defined in the IF part of the rule – that is not known to be true can be false or true. The differences between the two rules lie only in the last step, in which the order of values corresponding to the height of components and the calculated value are compared. Accordingly, the value of the checking property “cte_EHE08:50221_MinHeightCheck”, in the THEN part of the rule, is set true or false depending on whether the rule has to verify the compliance or non-compliance of the components. This way, the service will be able to read this information to decide whether it is necessary or not to suggest alternative products.

Other information can be included in the BIM model as a result of the application of this rule, independently of whether the rule is met or not. In this case, it was considered useful to include the minimum height calculated as additional information. This way, for instance, designers can be more aware of the exact height limits of each of these components according to the regulation.

Figure 5.14 shows the two above statements included in the THEN part of the rule.

```
PART 3: CONCLUSION (TO BE INCLUDED IN THE BIM MODEL).
        ->
        (?slabDummy cte_EHE08:50221_MinHeightCheck "true"^^xsd:boolean)
        (?slabDummy cte_EHE08:MinimumHeightBorder ?minimumHeightBorderValue)
```

Figure 5.14: Conclusion part of the rule with the RDF statements to be included in the BIM model if the condition is validated (PART 3).

After applying the rule, the service suggests valid alternative components for those cases in which the regulation is not fulfilled, by looking at the value of the checking property. If this is the case, alternative components from the BAUKOM catalogue are proposed. The query to access the catalogue is specified in a file that is provided externally to the service.

Figure 5.15 shows the information retrieved from the catalogue regarding the existing hollow-slab products. The first column of the data set includes the information about the height of components. Depending on the height value calculated by the formula, there will be a list of valid components with different heights. For example, if the calculated value is 36 cm, then the products with a height greater than this value will be listed. In this case, those with the following height values: 40.0, 50.0, 63.0 and 83.0.

```
height (meters), Weight (kN/m2), URI

{"16.0",    "2.695",    "http://www.baukom-catalog.org/companies/precat/products/LP16"},   //LP-16
{"20.0",    "2.891",    "http://www.baukom-catalog.org/companies/precat/products/LP20"},   //LP-20
{"25.0",    "3.577",    "http://www.baukom-catalog.org/companies/precat/products/LP25"},   //LP-25
{"32.0",    "4.508",    "http://www.baukom-catalog.org/companies/precat/products/LP32"},   //LP-32
{"40.0",    "5.0813",   "http://www.baukom-catalog.org/companies/precat/products/LP40"},   //LP-40
{"50.0",    "7.4235",   "http://www.baukom-catalog.org/companies/precat/products/LP50"},   //LP-50
{"63.0",    "9.6775",   "http://www.baukom-catalog.org/companies/precat/products/LP63"},   //LP-63
{"83.0",    "11.3092",  "http://www.baukom-catalog.org/companies/precat/products/LP83"}    //LP-83
```

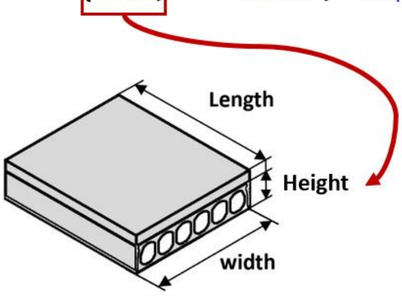


Figure 5.15: Information retrieved from the BAUKOM catalogue.

Information about alternative products is included in the RDF graph in the form of the following RDF statements (Figure 5.16):

```
rvtm:slab_1    rvt:hasSuggestedProduct        cat:LP40 ;
rvtm:slab_1    rvt:hasSuggestedProduct        cat:LP50 ;
rvtm:slab_1    rvt:hasSuggestedProduct        cat:LP63 ;
rvtm:slab_1    rvt:hasSuggestedProduct        cat:LP83 ;
```

Figure 5.16: Alternative references of products inferred.

The updated RDF graph of the BIM model resulting from the checking process can be stored, for example, in a file or in an online triple store (e.g., Fuseki or Virtuoso). BIM authoring tools, in this case Revit, can be linked to this service through a direct connection, for example through a plug-in facilitate the exchange of the BIM model in both directions. This way, the hollow-core slab components of the retrieved BIM model may include a new property with a value indicating the result of the checking. This last part is suggested as a possible extension of the implementation of the service.

5.5. Summary and conclusion

The purpose of this chapter was to conclude with the demonstration of the benefits in the use of Semantic Web technologies to improve the process of BIM modelling in building projects, by facilitating the link between BIM models and building components and products. To this aim, this chapter started by analysing the problem that arises when design team members from different disciplines participate in the creation of BIM models, taking decisions in their particular realms without considering the implications in other parts of the project. In the analysis of different alternatives to address this problem, the use of semantic inference rules applied in automated rule-based checking systems was investigated. In particular, the research focused on finding a method to apply these rules in a system capable of checking the components of BIM models and providing suggestions based on alternative valid products.

The design of a building needs to comply with a set of regulations and building codes that must be validated during the project. The verification of these regulations means that design team members must consult the information in different documents, interpreted and applied in the correct way. Although there are some applications that help to carry out this work, in general, this still requires spending time and effort. In principle, the interpretation and verification the building codes can be done more effectively in a BIM model than in previous 2D CAD drawings. However, greater capacity is required to apply the diversity of regulations, as well as to allow users to create new rules suited to a particular model. While some of these characteristics are starting to be included in specialized checking tools (e.g., Solibri Model Checker and Navisworks), there is still a lack of mechanisms to prevent the problem at its source, that is, during the design process.

In addition to providing models that meet building codes and standards from the outset, there is also the need for more optimized designs which take into account the constraints and requirements of the disciplines involved in the development of a building project (structural engineering; mechanical, electrical and plumbing; energy efficiency, and so on). The exchange of information across the different domains can be facilitated by rules, if these would be able to embed design intent and capture the experts' knowledge.

Some formulas and expressions used in calculation methods implemented in calculation tools, as well as those included in regulations, laws and building codes, can be extracted and encoded in inference rules. When these rules are described through rule languages based on Semantic Web technologies, that is, as semantic inference rules, some advantages can be achieved. Foremost among them is that these rules can be applied to infer conclusions about BIM models when their data are represented in RDF, taking advantage of its logical basis. The advantages in using these rules lies in their capability for reusability, as well as their flexibility for customization and linking information from different data sources provided in RDF through its encoding in the rule.

Considering the benefits in the use of semantic inference rules to check BIM models in RDF, a rule-checking and suggestion system was introduced in this chapter aimed at providing support to building designers in producing designs closer to the optimal solutions to be calculated in other disciplines. To this aim, two information domains were considered: regulations and products. In Section 5.3, main components of this system and how they are connected to provide this support was described. The system is based on a method and technical set-up for the creation and usage of inference rules implemented using Semantic Web technologies. These rules enable the data from these two domains to be linked when they are described in RDF and OWL languages. Processing these rules with reasoning engines enables new information to be inferred about BIM models. How information about a BIM model can be extracted and represented in RDF through ontological representations corresponding to the data structure of BIM authoring tools was discussed.

In Section 5.4, the implementation of a service prototype developed to validate the proposed method was introduced. Two examples were documented in which inference rules were created for the calculation of the pre-dimensioning and checking of hollow-core slab components as an application use case for structural modelling. With this service it is possible to reduce the number of iterations typically required between the architectural modelling programs and structural calculation programs.

The rule-checking and suggestion system involves the second part of the case study documented in this research. Figure 5.17 shows this part highlighted.

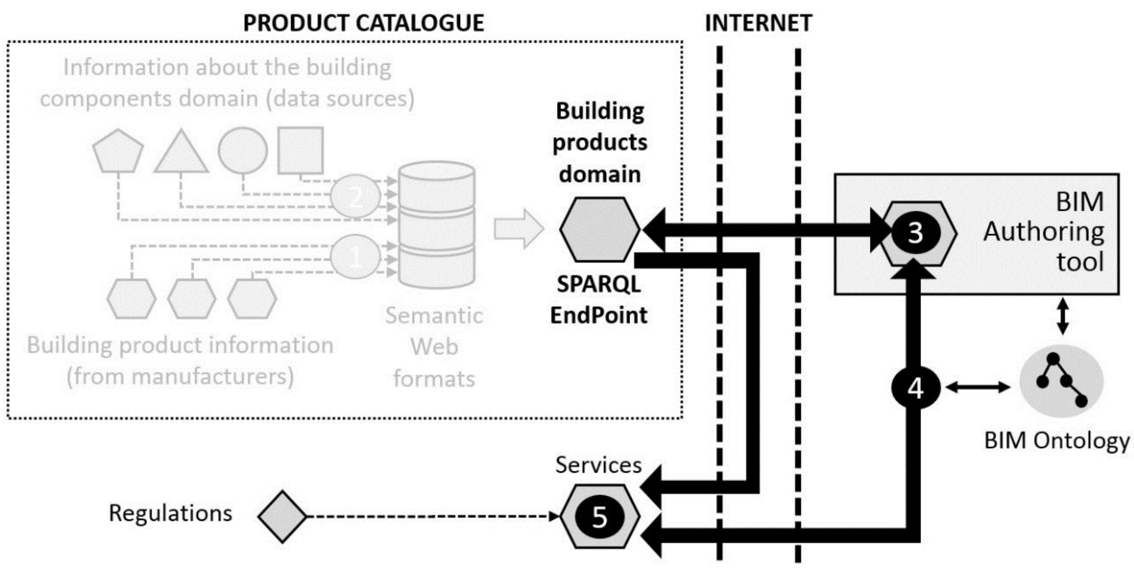


Figure 5.17: Highlighted is the second part of the case study covered in the development of the Rule-Checking and Suggestion System.

As a result of research in the context of the problem of redesigning, which has led to the proposal of a rule-checking and suggestion system, some conclusions can be outlined:

- With regard to its scope, the method developed in the rule-checking and suggestion system is generic enough. This means that the same method applied for the case of the hollow-core slab components can also be applied in the pre-dimensioning of other structural precast components, following the same procedure, or even in other domains (e.g., energy efficiency and acoustics).
- With regards to the advantages, one is greater modularity and flexibility to develop services (on the Web, plug-ins, etc.) capable of reusing data published in formats and technologies of the Semantic Web; services that can provide greater support for reasoning on BIM models.
- As for the current barriers to implement this system in the AEC industry, the most immediate is the lack of information about building products and regulations provided in the Semantic Web formats. This same problem was already discussed in the conclusions of Chapter 4 for the case of information about building components and products. In analysing the two domains: products and regulations, the second involves a number of limitations. First, only part of the content defined in the regulations is based on formulae and mathematical expressions that can be represented in computable rules. For the rest of the contents, approaches based on natural language processing (NLP) techniques have not yet proven to be very efficient. As for their availability, while the publication of information of products through the Semantic Web technologies is in the hands of the commercial interests of manufacturers, or intermediary agents, more susceptible and open to better ways to market their products, the publication of regulations is in the hands of public administrations.

6

Conclusion

This research started with the observation of some inefficiencies in the exchange of information between software applications in the AEC industry. In Chapter 2, these inefficiencies were examined in four dimensions: (1) collaboration, (2) methodologies, (3) interoperability, and (4) standards and technologies. In this context, collaboration refers to the way in which project participants with different backgrounds, experience and practice work together. Methodologies deal with the way in which participants, systems, business structures and practices are integrated in collaborative working processes. Interoperability comprises the ability to exchange information between software applications in a way that facilitates its use and interpretation by humans and machines. Finally, standards and technologies involve the mechanisms to facilitate interoperability in data exchange and, in general, to organize the information to make it more useful and interchangeable under a shared understanding.

The research in these four areas led to the conclusion that most of the inefficiencies in the exchange of information are due to the following reasons: the collaboration between agents is usually limited to the duration of a project; there is a difficulty in providing continuous flows of information through the work processes; the problems related to interoperability between software applications is not a priority for most BIM vendors; end users lack expertise and maturity in the use of BIM technologies; and methods to effectively extend the standard data models are missing. From a broader context, inefficiencies in data exchange are also due to factors such as culture, experience, business interests, or professional training, which are not always aligned with the search for standardized solutions to solve data exchange problems.

Other inefficiencies encountered in the exchange of information are related to technical and technological issues. It follows from them that interoperability problems between BIM applications are difficult to be resolved and probably will remain unresolved. One of the main problems that hamper interoperability is the heterogeneity existing between the data structures implemented in the software applications currently used in the AEC industry. The main reason for this heterogeneity is that applications are designed to respond to the needs of each type of discipline or task to be carried out in a building project. However, the design and construction of buildings usually requires the participation of different specialists for whom the software industry provides applications tailored to their needs. In the face of this situation, our investigation has led to consider the use of Semantic Web technologies, given their capabilities to explicitly and unambiguously define information through languages with a common logical basis which facilitates the integration of data from different sources and domains.

As a result, this led to the first research question:

RQ1. Can Semantic Web technologies be applied to provide long-term solutions to the pervading interoperability problems derived from the application of BIM in the AEC industry?

This question was addressed in the first line of research in this thesis. In Chapter 3, basic concepts about knowledge representation which underpin Semantic Web technologies were reviewed. Then, from the understanding of these concepts, we reviewed methods based on the application of these technologies in the AEC sector. Finally, the extent to which they have been successfully applied in actual projects was examined.

In the conclusion of Chapter 3, the main issues that led to the lack of interoperability outlined in the conclusion of Chapter 2 were discussed in more detail, and the extent to which Semantic Web technologies could help to overcome this problem. We saw that among the different types of interoperability involved in data exchange (syntax, structure, system and semantics), semantic interoperability still poses the greatest challenge. Semantic interoperability is essential to enable software agents to automatically and unambiguously interpret the exchanged information. Hence, interoperability standards such as IFC play a central role in providing a standardised semantic representation of a data domain. However, in the case of data exchange between BIM software applications, each with its own specific data model structure, it is difficult to create a standard data model that assures complete interoperability. Different strategies have been developed by standards such as IFC to reduce the size of the problem by addressing data interoperability within a particular scenario. However, the proposed solutions are still based on the vocabulary of the standard.

Semantic Web technologies can be applied to achieve data integration from multiple sources. In this case, these technologies provide methods to overcome the structural and semantic heterogeneity of data. Methods to integrate heterogeneous data are becoming increasingly necessary as there is a growing need for linking BIM data to other data sources. Currently, some of the information required in BIM software applications must be entered manually rather than being automatically obtained from the Web, for example, thus resulting in a manual, cumbersome, inefficient and error prone process.

When relying on the capabilities of Semantic Web technologies, information required from different data sources and domains can be unified within a specific domain. Data integration methods using these technologies were introduced and discussed in the last part of Chapter 3 (Section 3.3) as a plausible solution to provide the required interoperability. Building energy simulation was indicated as an example field in which information from different data sources is required. For instance, simulation tools and engines may require information from building designs, occupancy, and climate, among other domains, to perform a simulation. This information can be automatically integrated using a domain ontology (e.g., SimModel), in this case to satisfy the information needs of building energy simulation tools (e.g., EnergyPlus). However, there are more examples in which data integration may be required as in the combination of GIS data with BIM.

From the review of the role of ontologies in data integration methods, it can be concluded that it will become easier for software developers to reuse ontologies to facilitate data exchange, as an increasing number of those are created from existing standards (e.g. IFC, CityGML). Many of the efforts in this direction are currently focusing on the IFC standard. In Section 3.2.5, the development of ontologies from IFC schemas which gave rise to the ifcOWL ontology was reviewed. With this ontology, information of BIM models in IFC can be transformed and represented as RDF graphs. This can facilitate the integration of this information with other data sources, but it also has advantages for other purposes such as the creation of reasoning algorithms to perform rule-checking operations and facilitate decision-making.

The availability of existing converters that enable automating the transformation of the data defined according to the standards used in the AEC industry into RDF data can be useful to facilitate a part of the data integration process. However, the greatest difficulty is still the reconciliation of the data to be integrated and the target ontology. Although Semantic Web technologies and ontology engineering provide methods to automatically transform data from one ontology domain to another (e.g., using SPARQL CONSTRUCT queries), the process to obtain the correspondences (i.e., mappings) between the concepts required considerable human effort. Even though ontology matching techniques can facilitate the automatic discovery of mappings, these only provide partial results that need to be verified by domain experts. This leads to the conclusion that solutions based on data integration methods based on Semantic Web technologies will continue to require the collaboration of ontology engineers and domain experts.

After investigating the application of data integration methods based on semantic technologies to address the interoperability between software applications used in conjunction with BIM software, their capacities to improve the access, mixing, linkage and reuse of information outside a BIM model (e.g., product catalogues, repositories of BIM components, and building codes and regulations) were examined. Today, the consultation and collection of the information necessary for the development of projects still requires big efforts. Moreover, the information may have expired, be incomplete or it can be misinterpreted. Among this external information, the information about building components and products plays a prominent role in the development of building projects.

The analysis of methods to gather and integrate information about building components and products to make it accessible to BIM models led to the following two related research questions:

RQ2. Can manufacturers be involved in defining information about their products in Semantic Web formats? If so, in which ways and to obtain what benefits?

RQ3. Can product information be integrated with other related data sources to meet the needs of potential areas of application in the design and construction of buildings?

These two questions were addressed in Chapter 4. They form a second line of research concerned with providing methods to capture the knowledge of manufacturers and to combine it with other data sources. To this purpose, the requirements and usages of building component and product information in BIM modelling, the role of manufacturers in providing this information, and the process to capture and model their expertise were first examined. Second, the feasibility of data integration methods using Semantic Web technologies, taking into account the nature of the data and their accessibility was assessed. In examining this last question, it was found that information about building components and products remains scattered in different locations and formats, even in non-digitized ones. Consequently, design team members have to collect and interpret the information they need, for example, to decide which products are most suitable for their projects.

In the first part of Chapter 4, different aspects related to the use of information about building components and products in BIM-based projects were examined. For example, the requirements of this information at each stage of the design, depending on the type of project, discipline, and so on were discussed. The use of building components and products information was also investigated to facilitate their choice according to project requirements. Nowadays, there is growing need for more accurate and comprehensive information about the sustainability of building components in materials, their energy performance and their embedded energy, as well as their economic impact in the project. The existing tools which facilitate this kind of information are limited to a specific domain, to the data suppliers and to a geographic area. In other words generic solutions are not flexible enough to facilitate data integration across data domains and sources.

In many ways, the above limitations are similar to those observed in the analysis of the current web-based product catalogues. From the review of the most popular ones in Section 4.2, it was found that they do not provide mechanisms to personalize the information contained in the BIM objects of building products. Having objects described in multiple ways is necessary to meet the requirements of a particular discipline or a project phase. The format in which these BIM objects are provided is also an issue. There are a few BIM objects represented in IFC in the available catalogues because proprietary formats offer more confidence for seamless import into a particular software. Moreover, the catalogues examined do not provide mechanisms for querying information of building products in accordance with specific requirements (e.g., regulations, quality certificates and environmental data). One of the causes that makes it difficult to have more information available about products in these catalogues is the lack of mechanisms for manufactures to define the features of their products. Likewise, mechanisms are needed to relate product data with other building component data. Considering all these shortcomings and needs, the extent to which data integration methods based on Semantic Web technologies could provide a solution to these problems was investigated in closer detail.

Different types of data related to the domain of building components, integrated and provided in Semantic Web formats, can make it easier for agents involved in a building project to search and reuse the information through services created to support BIM modelling. This way, ad hoc services can be developed to access these data, taking advantage of the capabilities provided by these technologies. A product catalogue created with semantic technologies was developed in the BAUKOM project to demonstrate the potential benefits of these technologies (Section 4.3) by: (1) enabling manufacturers to specify the information of their products and (2) integrating this information with other data sources to facilitate an integrated access to information about building components and products. In the first case, the way in which the information of products can be described by manufacturers using a set of web-based interfaces was investigated. Since this information is mostly described through product data sheets, a specification method compatible with this format was proposed based on parametric data models. To enable this specification, it was introduced in Section 4.3.2 the methodology developed in BAUKOM to describe products following a two-level structure: templates and product definitions using these templates. The result is a standardized process to specify product data in a semantic format. In the second case, it was investigated how to integrate the product data introduced by the manufacturers with the data from multiple and heterogeneous sources.

As indicated in Section 4.3.3, information related to the domain of building components is currently dispersed and defined in different information systems and data formats. Moreover, some of the information has not yet been digitized. Therefore, a method was proposed to integrate this diversity of data. First, the information is transformed from a source format into a common domain, in this case a relational database model. Second, mappings to transform the information from this database model into RDF are generated following an ETL process. This two-step method enables specialists with different skills to intervene in each part of the process in accordance with their knowledge and skills. Its feasibility was demonstrated through an application case, documented in Section 4.3.3, to enable the integration of classification systems. Considering the characteristics of this integration process, a materialized integration approach was opted to reduce its complexity in case the data from a new source have to be integrated, and to increase reliability when the integrated data are queried.

Following the implementation and testing of the BAUKOM platform, some further improvements were pinpointed. Among them, the convenience to directly integrate in the catalogue the information that currently resides in the manufacturers' databases. This could be done, for example, through connectors compatible with the template-product model implemented in BAUKOM.

Once information is integrated and published on the Web using SPARQL endpoints, it can be accessed and retrieved remotely through SPARQL queries. This way, software services developed by third parties, for example developers of software for BIM modelling, can invoke the catalogue through SPARQL queries. This way, the catalogue can be considered one more data source available on the Web that can be accessed in accordance with the linked data philosophy.

Furthermore, semantic inference rules provide a mechanism to enable reasoning over this linked data. Our work on methods based on semantic inference rules for a more efficient use of product data in BIM-based projects led to the fourth and last research question addressed in this thesis:

RQ4. Can Semantic Web technologies be applied to improve the process of building design and modelling through the suggestion of building components and products?

This question was addressed in the last research line in which semantic inference rules were applied to check components of BIM models and to provide design team members suggestions for alternative products during the building design process. The first part of Chapter 5 described the context in which these rules could be useful. Considering that designers from different disciplines collaborate in the creation of a BIM model, it is essential to provide mechanisms to assure compatibility among the changes proposed by the different experts. The lack of congruency between these changes results in an inefficient design process. This problem becomes exacerbated as a result of the interoperability limitations between BIM models and other external applications.

To overcome these problems, in Section 5.3 the application of semantic inference rules to check the components of a BIM model and to provide a range of alternative components which suit the project requirements was proposed. The application of these rules was demonstrated in Section 5.3.2 by means of a system which (1) evaluates the structural safety requirements of BIM-model components, and (2) suggests alternative products that meet the same requirements. This demonstration case encompassed three data sources: BIM models, product data and building regulations. A prototype service for structural design with prefabricated concrete components (Section 5.4) was created as a proof of concept. RDF graph patterns derived from an ontology that models the information of a BIM model were linked to calculation formulas extracted from building regulations through semantic inference rules. In this way, two sets of inference rules were created to pre-dimension and check hollow-core slab components. Through the application of these rules, it is possible to infer the suitability and validity of the structural components inserted in the BIM model and to provide alternative components extracted from the BAUKOM catalogue which fulfilled the same requirements.

Three important features of this rule-checking system are its generality, modularity and flexibility. The system is generic in so far it can be applied to other structural precast components or even to other domains (e.g., energy efficiency and acoustics). It is modular because different modules can be developed implementing this system and combined depending on the BIM modelling needs using the appropriate set of rules. Finally, it is flexible because semantic rules can be modified and adapted to different contexts in a simple way, since they are independent of specific software applications.

Although this research has demonstrated the feasibility of applying Semantic Web technologies along with BIM-based processes, there are still important challenges that must be overcome to make their application widespread. One of them is the commitment of the leading manufacturers, product catalogue providers and public administrations to provide their data in Semantic Web formats to enable their open access, linkage and reuse. Furthermore, another challenge is to maintain the links between data sets. Mappings between ontologies must be updated whenever one of them is modified. For example, ontologies to model standards must be updated every time a new version is released. As a result, the mappings with other ontologies also need to be updated.

The work carried out in this thesis could continue along different lines of work. Regarding requirements of building components and products, more research is required to improve the automation of the mapping processes. From a technical standpoint, ontology-based data access (OBDA) systems – which use ontologies as mediator schemas to combine data stored in multiple heterogeneous sources – could be used to facilitate data querying could be explored. Furthermore, more user-friendly interfaces, including visual representation of ontologies, can also be considered as a further work. One option here could be the use of VOWL, “a well-specified visual language for the user-oriented representation of ontologies” (Lohmann, Negru, Haag, & Ertl, 2016). Visual graph representations can facilitate the identification of mappings between concepts or data structure patterns in different ontologies. This sort of visual representations can be particularly helpful for domain experts who are not ontology engineers. Here, the research work carried out by Sicilia, Nemirovski, and Nolle (2016) could be adapted for this case. Finally, a further recommendable application would be to apply the methods developed in BAUKOM to other case studies, with other kinds of building components, manufacturers and project requirements. Information about these components provided in the catalogue as RDF data accessible through the Web would be compatible with the data of other catalogues provided in this same format. However, to take full advantage of the ontology-driven applications that feed on these data, it would be desirable for all developers of these catalogues to adopt the same ontology to represent the information of this domain. In this sense, a possible future work would be to consider the ontology developed in BAUKOM as a basis for reaching a more consensual model for the domain of building products, filling some of the existing gaps. This could be achieved, for example, by sharing this work with W3C working groups. The adoption of a reference domain ontology to define the product data in BAUKOM-like catalogues could facilitate their reuse in BIM applications. Applications adopting this ontology could be implemented to feed on product data from the catalogues using the same method to access them and to facilitate their integration with the data from other building domains as needed.

Semantic Web technologies are expected to play an increasingly prominent role in data integration in the coming years, not only in the AEC sector. To carry out this integration, the use of loosely coupled domain models is presented as the dominant approach to address interoperability in federated data scenarios. By not forcing the models of different domains, which may have some relationship, to be fully linked, it is possible to combine their data for different purposes such as interoperability. An advantage is that domain models can evolve by extending them without affecting the applications that implement them. For example in BAUKOM, the ontology was extended to include the information of classifications. This approach also has similarities with some of the new trends in the development of software applications such as domain driven design (DDD), which advocates to connect the implementation to models that can evolve incrementally. Domain driven design facilitates a better collaboration between developers and domain experts.

Concerning the creation and use of inference rules to check BIM models using linked data, future work could aim at the development of an environment to facilitate the creation, editing and curation of the rules. This environment would provide access to ontologies so that semantic components required to create the rules could be easily located, selected and automatically included, which is still done manually. Furthermore, it would be appropriate to analyse the implications of the application of these rules in different cultural contexts. This is necessary because each country has its own building regulations and codes which are described in different languages. Besides, the BIM models can be specified differently in each cultural context, even though the software is the same. Semantic inference rules could help to overcome these interoperability problems derived from not from the data and tools but from the cultural differences.

7

References

Abdelmohsen, S. M. A. (2011). *An Ethnographically Informed Analysis of Design Intent Communication in BIM-Enabled Architectural Practice*. Georgia Institute of Technology.

Abdul-Ghafour, S., Ghodous, P., Shariat, B., & Perna, E. (2008). Towards an Intelligent CAD Models Sharing Based on Semantic Web Technologies. In R. Curran, S.-Y. Chou, & A. Trappey (Eds.), *Collaborative Product and Service Life Cycle Management for a Sustainable World* (pp. 195–203). Springer London. Retrieved from http://dx.doi.org/10.1007/978-1-84800-972-1_18.

AEC (UK) Committee. (2015). *AEC (UK) BIM Technology Protocol, Practical implementation of BIM for the UK Architectural, Engineering and Construction (AEC) industry*.

Afsari, K., & Eastman, C. (2014). Categorization of building product models in BIM Content Library portals. *XVII Cogreso de La Sociedad Iberoamericana de Gráfica Digital*, *1*(8), 370–374.

AIA. (2007). Integrated Project Delivery: A Guide. *American Institute of Architects*, 1–62. http://doi.org/10.1016/j.autcon.2010.09.002.

AIA. (2008). AIA E203-2013, Building Information Modeling and Digital Data Exhibit. Retrieved from http://www.aia.org/digitaldocs.

AIA. (2013). AIA G202-2013, Project Building Information Modeling Protocol Form. AIA Contract Document G202–-2013, Building Information Modeling Protocol Form. Retrieved from http://www.aia.org/digitaldocs.

Aish, R. (1986). Building modeling: the key to integrated construction CAD. In *CIB 5th International Symposium on the Use of Computers for Environmental Engineering Related to Buildings* (Vol. 5, pp. 7–9).

Aish, R., & Woodbury, R. (2005). Multi-Level Interaction in Parametric Design. In *International symposium on smart graphics* (pp. 151–162). Heidelberg, Springer Berlin. http://doi.org/10.1007/11536482_13.

Alexander, K., Cyganiak, R., Hausenblas, M., & Zhao, J. (2011). Describing Linked Datasets with the VoID Vocabulary. *W3C Interest Group Note 03 March 2011*, (March), 1–37. Retrieved from http://www.w3.org/TR/void.

Ali, A. S., & Rahmat, I. (2009). Methods of coordination in managing the design process of refurbishment projects. *Journal of Building Appraisal*, *5*(1), 87–98.

Allemang, D., & Hendler, J. (2011). *Semantic Web for the Working Ontologist: Effective modeling in RDFS and OWL*. (D. J. H. Allemang, Ed.), *Semantic Web for the Working Ontologist*. elsevier. http://doi.org/10.1016/B978-0-12-385965-5.10016-0.

An, Y., Borgida, A., & Mylopoulos, J. (2005). Inferring complex semantic mappings between relational tables and ontologies from simple correspondences. In *On the Move to Meaningful Internet Systems 2005: CoopIS, DOA, and ODBASE* (Vol. 3761, pp. 1152–1169). Springer Berlin Heidelberg. http://doi.org/10.1007/11575801_15.

Andia, A. (2013). Automate Architecture. In E. Berman, I. Mitchell (Ed.), *101st Annual Meeting of the Association of Collegiate Schools of Architecture (ACSA)* (pp. 184–192). Washington, DC.

Arayici, Y., & Aouad, G. (2011). Building information modelling (BIM) for construction lifecycle management. In *Construction and Building: Design, Materials, and Techniques* (pp. 99–117). New York: Nova Science Publishers. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-84862000037&partnerID=tZOtx3y1.

Arenas, M., Bertails, A., Prud'hommeaux, E., & Sequeda, J. F. (2011). A Direct Mapping of Relational Data to RDF. *W3C Working Draft 20 September 2011*. Retrieved from https://www.w3.org/TR/2011/WD-rdb-direct-mapping-20110920.

Astrova, I., Korda, N., & Kalja, A. (2007). Rule-Based Transformation of SQL Relational Databases to OWL Ontologies. In *2nd International Conference on Metadata and Semantics Research* (pp. 1–16). Corfu.

Aumueller, D., Do, H. H., Massmann, S., & Rahm, E. (2005). Schema and ontology matching with COMA++. In *ACM SIGMOD international conference on Management of data* (pp. 906–908). New York: ACM Press. http://doi.org/http://doi.org/10.1145/1066157.1066283.

Bank, L. C., Thompson, B. P., & McCarthy, M. (2011). Decision-making tools for evaluating the impact of materials selection on the carbon footprint of buildings. *Carbon Management*, *2*(4), 431–441.

Barrasa-Rodríguez, J. B., & Gómez-Pérez, A. (2006). Upgrading relational legacy data to the semantic web. In *15th international conference on World Wide Web* (pp. 1069–1070). ACM.

Beckett, D., & Berners-Lee, T. (2008). Turtle - Terse RDF Triple Language. *W3C Team Submission*. Retrieved from http://www.w3.org/TeamSubmission/turtle.

Beckett, D., & McBride, B. (2004). RDF/XML syntax specification (revised). In *W3C recommendation* (Vol. 10). Retrieved from https://www.w3.org/TR/REC-rdf-syntax.

Bedrick, J. (2013). A Level of Development Specification for BIM Processes. *AECbytes Viewpoint*. Retrieved from http://www.aecbytes.com/viewpoint/2013/issue_68.html.

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

Beetz, J., & de Vries, B. (2009). Building Product Catalogues on the Semantic Web. In *26th International Conference on Information Technology in Construction CIB W78* (pp. 221–226).

Beetz, J., Leeuwen, J. P., & Vries, B. (2005a). An Ontology Web Language Notation of the Industry Foundation Classes. In *22nd CIB W78 Conference on Information Technology in Construction* (pp. 193–198).

Beetz, J., Leeuwen, J. P. Van, & Vries, B. De. (2005b). An Ontology Web Language Notation of the Industry Foundation Classes. *Proceedings of the 22nd CIB W78 Conference on Information Technology in Construction*, 193–198.

Beetz, J., van Leeuwen, J., & de Vries, B. (2009). IfcOWL: A case of transforming EXPRESS schemas into ontologies. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, *23*(1), 89–101.

Bell, H., & Bjørkhaug, L. (2006). A buildingSMART ontology. In *6th European Conference on Product and Process Modelling (ECPPM)* (pp. 185–190).

Berners-Lee, T. (1998). Semantic Web Road map. *Design Issues for the World Wide Web*. Retrieved from http://www.w3.org/DesignIssues/Semantic.html.

Berners-Lee, T. (2006a). Linked Data Design Issues. *W3C*. http://doi.org/10.1145/1367497.1367760.

Berners-Lee, T. (2006b). Semantic Web Technologies Stack. Retrieved from http://www.w3.org/DesignIssues/diagrams/sweb-stack/2006a.png.

Berners-Lee, T., & Connolly, D. (2011). Notation3 (N3): A readable RDF syntax. *W3C Team Submission. World Wide Web Consortium*. Retrieved from http://www.w3.org/TeamSubmission/n3.

Bevill, D., & Arsenault, P. J. (2010). *Building Information Modeling (BIM) and Building Product Manufacturers*.

Bew, M., & Richards, M. (2008). BIM maturity model. In *Construct IT Autumn 2008 Members*. Brighton.

BIMForum. (2015). Level of Development Specification, Version 2015. Retrieved from www.bimforum.org/lod.

Bizer, C., & Schultz, A. (2010). The R2R Framework: Publishing and Discovering Mappings on the Web. *First International Conference on Consuming Linked Data*, *665*, 97–108.

Bizer, C., & Cyganiak, R. (2006). D2R Server – Publishing Relational Databases on the Semantic Web. *Poster at the 5th International Semantic Web Conference (ISWC2006)*.

Bizer, C., Heath, T., & Berners-Lee, T. (2009). Linked data-the story so far. *International Journal on Semantic Web and Information Systems*, *5*(3), 1–22. http://doi.org/10.4018/jswis.2009081901.

Bizer, C., & Seaborne, A. (2004). D2RQ – Treating Non-RDF Databases as Virtual RDF Graphs. In *3rd international semantic web conference (ISWC2004)* (p. 26). Springer.

http://doi.org/10.1.1.126.2314.

Björk, B. C. (1992). A unified approach for modelling construction information. *Building and Environment*, *27*(2), 173–194. http://doi.org/10.1016/0360-1323(92)90021-G.

Björk, B. C. (1995). *Requirements and information structures for building product data models*. *VTT Publications*. VTT Technical Research Centre of Finland, Espoo.

Björk, B. C. (2009). Ratas, a longitudinal case study of an early construction it roadmap project. *Electronic Journal of Information Technology in Construction*, *14*, 385–399.

Björk, B. C., & Penttilä, H. (1989). A scenario for the development and implementation of a building product model standard. *Advances in Engineering Software and Workstations*, *11*(4), 176–187. http://doi.org/10.1016/0141-1195(89)90049-1.

Bjørkhaug, L. (2003). Use of building product models and reference data libraries for project and quality management. In *Construction Project Management Systems: The Challenge of Integration*. iin-house publishing. Retrieved from http://www.irbnet.de/daten/iconda/CIB1507.pdf.

Böhms, H. M. (2007). Semantic Web-based Open engineering Platform (SWOP).

Böhms, H. M., Plokker, W., Charvier, B., Madrazo, L., & Sicilia, A. (2010). IntUBE energy information integration platform. In K. Menzel & R. J. Sherer (Eds.), *8th European Conference on Product and Process Modelling (ECPPM)* (pp. 339–344). Cork: CRC press.

Böhms, M., Bonsma, P., Bourdeau, M., & Samad, A. (2009). Semantic product modelling and configuration: Challenges and opportunities. *Electronic Journal of Information Technology in Construction*, *14*, 507–525.

Boley, H., Dean, M., Grosof, B., Sintek, M., Spencer, B., Tabet, S., & Wagner, G. (2005). FOL RuleML: The First-Order Logic Web Language. Retrieved from https://www.w3.org/Submission/FOL-RuleML/.

Bonsma, P., Bonsma, I., Zayakova, T., & Böhms, M. (2014). *Semantic web platform and interfaces*. Retrieved from http://www.proficient-project.eu/.

Bouras, T., Gouvas, P., & Mentzas, G. (2008). Dynamic Data Mediation in Enterprise Application Integration. In *eChallenges e-2008 Conference* (pp. 917–924). Stockholm.

Breaux, T. D., Vail, M. W., & Antón, A. I. (2006). Towards regulatory compliance: Extracting rights and obligations to align requirements with regulations. In *14th International Requirements Engineering Conference (RE'06)* (pp. 46–55).

Brickley, D., & Guha, R. V. (2004). RDF vocabulary description language 1.0: RDF schema. W3C recommendation. Retrieved from http://www.w3.org/TR/rdf-schema/.

Brickley, D., & Miller, L. (2000). FOAF: friend of a friend. Retrieved from http://www.foaf-project.org/.

Buccella, A., Cechich, A., & Brisaboa, N. R. (2003). An Ontology Approach to Data Integration. *Journal of Computer Science & Technology*, *3*(2), 62–68.

BuildingSMART. (2015). ifcOWL. Retrieved from http://www.buildingsmart-tech.org/future/linked-data/ifcowl.

Bussler, C. (2003). The Role of Semantic Web Technology in Enterprise Application Integration. *IEEE Data Engineering Bulletin*, *26*(4), 62–68.

Chaparala, R. T., Hartman, N. W., & Springer, J. (2013). Examining CAD interoperability through the use of ontologies. *Computer-Aided Design and Applications*, *10*(1), 83–96.

Cheng, C. P., Lau, G. T., & Law, K. H. (2007). Mapping regulations to industry-specific taxonomies. *11th International Conference on Artificial Intelligence and Law*, 59–63. Retrieved from http://portal.acm.org/citation.cfm?doid=1276318.1276329.

Cheng, C. P., Lau, G. T., Law, K. H., Pan, J., & Jones, A. (2008). Regulation retrieval using industry specific taxonomies. *Artificial Intelligence and Law*, *16*(3), 277–303.

Cheptsov, A. (2011). Semantic Web Reasoning on the Internet Scale with Large Knowledge Collider. *International Journal of Computer Science and Applications, Technomathematics Research Foundation*, *8*(2), 102–117.

Choi, J., & Kim, I. (2016). Development of BIM-based Quality Checking System through Building Code Criteria. In *Asia-pacific Proceedings of Applied Science and Engineering for Better Human Life* (Vol. 2, pp. 78–81).

CIBSE. (2015). Product Data Template. Retrieved from http://www.cibse.org/knowledge/bim-building-information-modelling/product-data-templates/published-pdts.

CIC. (2010). BIM Project Execution Planning Guide, Version 2.0. CIC Research Group, Pennsylvania State University.

Clark, J. (1976). Hierarchical geometric models for visible surface algorithms. *Communications of the ACM*, *19*(10), 547–554.

CMAA. (2012). An owner's guide to project delivery methods. The Construction Management Association of America. Retrieved from https://cmaanet.org/files/Owners Guide to Project Delivery Methods Final.pdf.

Coloma, E. (2011). *BIM Tecnology from a Designer point of view*. Polytechnic University of Catalonia.

Compton, M., Barnaghi, P., Bermudez, L., GarcíA-Castro, R., Corcho, O., Cox, S., … Taylor, K. (2012). The SSN ontology of the W3C semantic sensor network incubator group. *Web Semantics: Science, Services and Agents on the World Wide Web*, *17*, 25–32. Retrieved from https://www.w3.org/2005/Incubator/ssn/.

Conover, D., Barnaby, C. S., Crawley, D., Gulledge, C., Hagan, S., Hitchcock, R., … Iverson, D. (2009). An Introduction to Building Information Modeling (BIM): A Guide for ASHRAE Members. Atlanta: ASHRAE.

Corcho, O. (2005). *A layered declarative approach to ontology translation with knowledge preservation (Frontiers in Artificial Intelligence and its Applications. Dissertations in Artificial Intelligence)*. IOS Press.

Corry, E., Coakley, D., O'Donnell, J., & Keane, M. M. (2013). The role of Linked Data and the Semantic Web in Building Operation. *13th Annual International Conference for Enhanced Building Operations (ICEBO)*, 70.

Costa, G., & Madrazo, L. (2014). An information system architecture to create building components catalogues using semantic technologies. In A. Mahdavi, B. Martens, & R. Scherer (Eds.), *10th European Conference on Product & Process Modelling*

(ECPPM) (pp. 551–558). Vienna: CRC press. http://doi.org/10.1201/b17396-90.

Costa, G., & Madrazo, L. (2015). Connecting building component catalogues with BIM models using semantic technologies: an application for precast concrete components. *Automation in Construction*, *57*, 239–248. http://doi.org/10.1016/j.autcon.2015.05.007

Costa, G., & Pauwels, P. (2015). Building product suggestions for a BIM model based on rule sets and a semantic reasoning engine. In *32rd international CIB W78 conference* (pp. 98–107).

Costa, G., Rodríguez, M., Jardí, A., Vidoni, D., Delgado, D., Sagredo, L., … Martín, A. (2016). Práctica Integrada, interoperabilidad y uso del BIM en el sector de la construcción. Barcelona: BIM user group of Catalonia. Retrieved from http://gubimcat.blogspot.com.es/2016/05/encuesta-sobre-practica-integrada.html.

Costa, G., Sicilia, Á., Lilis, G., Rovas, D., & Izkara, J. (2016). A comprehensive ontologies-based framework to support retrofitting design of energy-efficient districts. In S. Christodoulou & R. Scherer (Eds.), *11th European Conference on Product & Process Modelling (ECPPM)* (pp. 673–681). Limassol: CRC press.

Costa, G., Valderrama, J., & Jardí, A. (2016). HACIA UN MODELADO BIM A TRAVÉS DE LA NUBE Y CON DATOS ENLAZADOS. In B. Giner & I. Faubel (Eds.), *Congreso Internacional BIM/5º Encuentro de Usuarios BIM (EUBIM)* (pp. 125–137). Valencia: Polytechnic University of Valencia. http://doi.org/10.4995/EUBIM.2016.4244

Cross, N. (2006). *Designerly ways of knowing*. *Designerly Ways of Knowing*. Springer London.

Curry, E., O'Donnell, J., Corry, E., Hasan, S., Keane, M., & O'Riain, S. (2013). Linking building data in the cloud: Integrating cross-domain building data using linked data. *Advanced Engineering Informatics*, *27*(2), 206–219. http://doi.org/10.1016/j.aei.2012.10.003.

Cyganiak, R., & Jentzsch, A. (2011). The linking open data cloud diagram. LOD Community. Retrieved from http://lod-cloud.net/

Das, S., Sundara, S., & Cyganiak, R. (2012). R2RML: RDB to RDF mapping language. Retrieved from http://www.w3.org/TR/r2rml/.

Davies, M. (2015). Knowledge (Explicit, Implicit and Tacit): Philosophical Aspects. In *International Encylopedia of the Social & Behavioral Sciences (Second Edition)* (pp. 74–90). http://doi.org/10.1016/B978.

Davis, D. (2010). A Standardized Structure for Defining and Managing BIM Project Deliverables. AEC Infosystems, Inc. Retrieved from http://www.aia.org/-aiaucmp/groups/aia/documents/pdf/aiab086677.pdf.

Davis, D. (2013). *Modelled on Software Engineering: Flexible Parametric Models in the Practice of Architecture*. RMIT University.

Day, M. (2011). The trouble with BIM, Building Information Modelling (BIM) for Architecture, Engineering and Construction. *AEC Magazine*. Retrieved from http://aecmag.com/technology-mainmenu-35/450-the-trouble-with-bim.

Day, M. (2014). The problem with COBie. *AEC Magazine*. Retrieved from http://aecmag.com/technology-mainmenu-35/598-the-problem-with-cobie.

De Bruijn, J., Ehrig, M., Feier, C., Martíns-Recuerda, F., Scharffe, F., & Weiten, M. (2006). Ontology Mediation, Merging, and Aligning. In *Semantic Web Technologies: Trends and Research in Ontology-based Systems* (pp. 95–113). John Wiley & Sons, Ltd.

de Medeiros, L. F., Priyatna, F., & Corcho, O. (2015). MIRROR: Automatic R2RML Mapping Generation from Relational Databases. In P. Cimiano, F. Frasincar, G. J. Houben, & D. Schwabe (Eds.), *International Conference on Web Engineering* (pp. 326–343). Rotterdam: Springer International Publishing. http://doi.org/http://doi.org/10.1007/978-3-319-19890-3_21.

De Nicola, A., & Missikoff, M. (2016). A lightweight methodology for rapid ontology engineering. *Communications of the ACM*, *59*(3), 79–86. http://doi.org/10.1145/2818359.

De Roo, J. (2012). EYE engine. Retrieved from http://eulersharp.sourceforge.net/.

Deborah, L., & Van McGuinness, F. (2004). OWL Web Ontology Language overview. W3C recommendation. Retrieved from https://www.w3.org/TR/owl-features/.

Degeler, V., Gonzalez, L. I. L., Leva, M., Shrubsole, P., Bonomi, S., Amft, O., & Lazovik, A. (2013). Service-Oriented Architecture for Smart Environments. In *6th International Conference on Service-Oriented Computing and Applications (SOCA)* (pp. 99–104). IEEE. http://doi.org/10.1109/SOCA.2013.26.

Demir, S., Garrett, J. H., Akinci, B., Akin, O., & Palmer, M. (2010). A semantic web-based approach for representing and reasoning with vocabulary for computer based standards processing. In *2010 International Conference on Computing in Civil and Building Engineering (ICCCBE'10)*. Nottingham.

Dikbas, A., & Ercoskun, K. (2006). Construction information classification: an object oriented paradigm. In M. Martíinez & R. Scherer (Eds.), *6th European Conference on Product & Process Modelling (ECCPM)* (pp. 317–325). Taylor & Francis/Balkema.

Dimyadi, J., & Amor, R. (2013). Regulatory Knowledge Representation for Automated Compliance Audit of BIM-based models. In *30th CIB W78 International Conference* (pp. 68–78).

Ding, L., Drogemuller, R., Rosenman, M., Marchant, D., & Gero, J. (2006). Automating code checking for building designs - DesignCheck. In K. Brown, K. Hampson, & P. Brandon (Eds.), *Clients Driving Construction Innovation: Moving Ideas into Practice*. Brisbane: CRC for Construction Innovation.

Ding, Y., van Rijsbergen, C. J., Ounis, I., & Jose, J. (2003). *Report on ACM SIGIR Workshop on 'Semantic Web' SWIR 2003*. Toronto.

East, E. W. (2007). Construction Operations Building Information Exchange (Cobie): Requirements Definition and Pilot Implementation Standard (No. ERDC/CERL TR-07-30). Washington, DC: U.S. Army Corps of Engineers.

Eastman, C., Fisher, D., Lafue, G., Lividini, J., Stoker, D., & Yessios, C. (1974). *An Outline of the Building Description System. Research Rep, 50.* Pittsburgh.

Eastman, C., Lee, J. M., Jeong, Y., & Lee, J. K. (2009). Automatic rule-based checking of building designs. *Automation in Construction*, *18*(8), 1011–1033. http://doi.org/10.1016/j.autcon.2009.07.002

Eastman, C. M. (1975). The Use of Computers Instead of Drawings in Building Design. *AIA Journal*, *63*(3), 46–50.

Eastman, C. M. (1999). *Building product models: computer environments, supporting design and construction*. Atlanta: CRC press.

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*. *Building* (2nd ed.). John Wiley & Sons. http://doi.org/10.1002/9780470261309.

Edvardsen, D. F., Beetz, J., Lundkvist, A., Lindbäck, L., Hecher, M., Tamke, M., … Dietze, S. (2016). *D8.8 Dissemination Report Year 3, DURAARK No.: 600908*. Retrieved from http://duraark.eu/.

Eichert, J., & Kazi, A. S. (2007). Vision and strategy of ManuBuild - Open Building Manufacturing. In *Open Building Manufacturing – Core Concepts and Industrial Requirements* (pp. 5–14). Espoo.

EIF. (2012). What is semantic interoperability? Retrieved from https://joinup.ec.europa.eu/asset/page/practice_aids/what-semantic-interoperability.

Ekholm, A., & Häggström, L. (2011). Building classification for BIM: Reconsidering the framework. In *28th CIB W78 and 6th CIB W102 International Conference* (pp. 26–28). Sophia.

Elvin, G. (2007). *Integrated practice in architecture: mastering design-build, fast-track, and building information modeling*. John Wiley & Sons.

Elvin, G. (2010). Principles of integrated practice in architecture. *Journal of Architectural and Planning Research*, *27*(4), 287–300.

Esfahani, N. N., Fuchs, S., & Scherer, R. (2014). Infrastructure and geospatial data models; spatial links. In A. Mahdavi, B. Martens, & R. Scherer (Eds.), *10th European Conference on Product & Process Modelling (ECPPM)*. CRC press. http://doi.org/10.1201/b17396-58.

European Commission. (2012). Delivering savings for Europe: moving to full e-procurement for all public purchases by 2016. Brussels: Press Release. Retrieved from http://europa.eu/rapid/press-release_IP-12-389_en.htm.

Euzenat, J., & Shvaiko, P. (2007). *Ontology matching*. Springer Berlin Heidelberg. http://doi.org/10.1007/978-3-540-49612-0.

Farias, M. T., Roxin, A., & Nicolle, C. (2014). A rule based system for semantical enrichment of building information exchange. In *CEUR Workshop Proceedings* (Vol. 1211, pp. 2–9). CEUR-WS.

Fensel, D., Van Harmelen, F., Klein, M., Akkermans, H., Broekstra, J., Fluit, C., … Others. (2000). On-to-knowledge: Ontology-based tools for knowledge management. In *eBusiness and eWork* (Vol. 82, pp. 18–20). Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.25.360&rep=rep1&type=pdf.

Fernández, M., Gómez-Pérez, A., & Juristo, N. (1997). METHONTOLOGY: From Ontological Art towards Ontological Engineering. In *AAAI Symposium on Ontological Engineering*. Stanford.

Fiorelli, M., Pazienza, M. T., & Stellato, A. (2014). A Meta-data Driven Platform for

Semi-automatic Configuration of Ontology Mediators. In N. Calzolari, K. Choukri, T. Declerck, H. Loftsson, B. Maegaard, J. Mariani, … S. Piperidis (Eds.), *9th International Conference on Language Resources and Evaluation (LREC)* (pp. 4178–4183). Reykjavik: European Language Resources Association (ELRA).

Fraunhofer IRB. (2011). The International CONstruction DAtabase: Retrieval of Planning & Building Related Publications. Stuttgart. Retrieved from https://www.irb.fraunhofer.de/iconda.

Fuentes, B. (2014). *Impacto de BIM en el proceso constructivo español*. Editorial Servicios y Comunicación IGV SL.

Gallaher, M. P., O’Conor, A. C., Dettbarn, J. L., & Gilday, L. T. (2004). Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry. In *National Institute of Standards and Technology (NIST)*. NIST Report No. GCR 04-867. http://doi.org/10.6028/NIST.GCR.04-867.

Geraci, A., Katki, F., McMonegal, L., Meyer, B., & Porteous, H. (1991). IEEE Standard Computer Dictionary. A Compilation of IEEE Standard Computer Glossaries. *IEEE Press*. http://doi.org/10.1109/IEEESTD.1991.106963.

Ghawi, R., & Cullot, N. (2007). Database-to-Ontology Mapping Generation for Semantic Interoperability. In *3th International Workshop on Database Interoperability (InterDB)*. Vienna. Retrieved from VLDB Endowment, ACM

Golbreich, C., Wallace, E. K., & Patel-Schneider, P. F. (2012). OWL 2 Web Ontology Language New Features and Rationale (Second Edition). W3C Recommendation. Retrieved from https://www.w3.org/TR/owl2-new-features/.

Gray, R. L. (2003). Brief Historical Review of the Development of the Distinction Between Data and Information. In J. Ross & D. Galletta (Eds.), *9th Americas Conference on Information Systems* (pp. 2843–2849). Association for Information Systems.

Gregor, S., & Hart, D. (2007). *Information Systems II: theory, representation and reality*. Canberra: ANU Press.

Gruber, T. R. (1993). A translation approach to portable ontology specifications. *Knowledge Acquisition*, *5*(2), 199–220. Retrieved from http://doi.org/10.1006/knac.1993.1008

Guarino, N., Oberle, D., & Staab, S. (2009). What Is an Ontology? Handbook on Ontologies. In *Handbook on Ontologies SE - International Handbooks on Information Systems* (pp. 1–17). Springer Berlin Heidelberg. http://doi.org/10.1007/978-3-540-92673-3_0.

Gudnason, G., & Pauwels, P. (2016). SemCat: Publishing and Accessing Building Product Information as Linked Data. In S. Christodoulou & R. Scherer (Eds.), *11th European Conference on Product & Process Modelling (ECPPM)* (pp. 659–666). Limassol: CRC press.

Guruz, R., Katranuschkov, P., Scherer, R., & Geissler, M. C. (2014). *ICT platform for holistic energy efficiency simulation and lifecycle management of public use facilities. HESMOS final booklet*. Retrieved from http://hesmos.eu/.

Hale, D. P., Woolridge, R. W., & Stogner, C. R. (2008). Sustaining the Nation’s Aging Infrastructure Systems: Lessons Learned Applying an Asset Management

Framework. In *Alfred P. Sloan Foundation Industries Studies Conference 2008* (pp. 1–20).

Hannus, M., Penttilä, H., & Silén, P. (1987). Islands of Automation. Retrieved from http://cic.vtt.fi/hannus/islands/index.html.

Harris, C. M. (2005). *Dictionary of architecture and construction* (4th ed.). McGraw-Hill Professional.

Harris, S., & Eaborne, A. (2010). SPARQL Query Language 1.1. Retrieved from https://www.w3.org/TR/2010/WD-sparql11-query-20100126/#construct.

Hayes, J. (2004). *A graph model for RDF*. *Darmstadt University of Technology / University of Chile*.

Hendler, J. J. A., & van Harmelen, F. (2008). The Semantic Web : Webizing Knowledge Representation. In F. van Harmelen, V. Lifschitz, & B. Porter (Eds.), *Handbook of Knowledge Representation* (1st ed., pp. 821–840). Elsevier. http://doi.org/10.1016/S1574-6526(07)03021-0.

Hepp, M. (2008). GoodRelations: An Ontology for Describing Products and Services Offers on the Web. In A. Gangemi & E. Jérôme (Eds.), *16th International Conference on Knowledge Engineering and Knowledge Management (EKAW)* (pp. 329–346). Acitrezza: Springer Berlin Heidelberg. http://doi.org/10.1007/978-3-540-87696-0_29.

Hepp, M. . (2011). Goodrelations language reference. Retrieved from http://www.heppnetz.de/ontologies/goodrelations/v1.

Herman, I., Adida, B., Sporny, M., & Birbeck, M. (2015). RDFa 1.1 Primer - Third Edition. Retrieved from https://www.w3.org/TR/xhtml-rdfa-primer/.

Hietanen, J. (2006). *IFC model view definition format*. *Technical Report. International Alliance for Interoperability*.

Holsapple, C. W., & Joshi, K. D. (2002). A collaborative approach to ontology design. *Communications of the ACM*, *45*(2), 42–47. Retrieved from http://dl.acm.org/citation.cfm?id=503147.

Horrocks, I., Kutz, O., & Sattler, U. (2006). The Even More Irresistible SROIQ. In *10th International Conference on Principles of Knowledge Representation and Reasoning (KR2006)* (pp. 57–67). AAAI Press.

Horrocks, I., Patel-Schneider, P. F., Bechhofer, S., & Tsarkov, D. (2005). OWL rules: A proposal and prototype implementation. *Web Semantics: Science, Services and Agents on the World Wide Web*, *3*(1), 23–40.

Horrocks, I., Patel-schneider, P. F., Boley, H., Tabet, S., Grosof, B., & Dean, M. (2004). SWRL : A Semantic Web Rule Language Combining OWL and RuleML. *W3C Member Submission*.

Horrocks, I., & Voronkov, A. (2006). Reasoning support for expressive ontology languages using a theorem prover. In *Foundations of Information and Knowledge Systems. Lecture Notes in Computer Science* (Vol. 3861, pp. 201–218). Springer Berlin Heidelberg.

Iadanza, E., Turillazzi, B., Terzaghi, F., Marzi, L., Giuntini, A., & Sebastian, R. (2015). The STREAMER European Project. Case Study: Careggi Hospital in Florence. In *6th European Conference of the International Federation for Medical and*

Biological Engineering (pp. 649–652). Springer International Publishing.

IDABC. Enterprise & Industry DG. (2004). European interoperability framework for pan-European e-government services. Belgium: European Communities.

Ingle, A., & Waghmare, A. P. (2015). Advances in Construction: Lean Construction for Productivity enhancement and waste minimization. *Engineering and Applied Sciences (IJEAS)*, *2*(11), 19–23.

Inmon, W. H. (1992). *Building the Data Warehouse*. New York: John Wiley & Sons, Inc.

ISES. (2014). Intelligent Services For Energy-Efficient Design and Life Cycle Simulation. Retrieved from http://ises.eu-project.info/.

ISO 10303-11:2004. (2004). Industrial automation systems and integration - Product data representation and exchange - Part 11: Description methods: The EXPRESS language reference manual. Retrieved from http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=25097.

ISO 10303-21:2016. (2016). Industrial automation systems and integration -- Product data representation and exchange -- Part 21: Implementation methods: Clear text encoding of the exchange structure.

ISO 12006-3:2007. (2007). Building construction - Organization of information about construction works - Part 3: Framework for object-oriented information. Retrieved from http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=38706.

ISO 16739:2013. (2013). Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries. Retrieved from http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=51622.

Jain, S., & Augenbroe, G. (2003). A Methodology for supporting product selection from E-catalogues. *Special Issue on eWork and eBusiness, Electronic Journal of Information Technology in Construction (ITcon)*, *8*, 383–396.

Jansche, M. (2005). Maximum expected F-measure training of logistic regression models. In *2005 Conference on Human Language Technology and Empirical Methods in Natural Language Processing* (pp. 692–699). Association for Computational Linguistics.

Jernigan, F. E. (2008). *Big BIM, little bim: the practical approach to building information modeling: integrated practice done the right way!* (2nd ed.). 4site Press.

Jiménez-Ruiz, E., Kharlamov, E., Zheleznyakov, D., Horrocks, I., Pinkel, C., Skjæveland, M. G., … Mora, J. (2015). BootOX: Practical Mapping of RDBs to OWL 2. In *14th International Semantic Web Conference on The Semantic Web - ISWC* (Vol. 9367, pp. 113–132). Bethlehem: Springer International Publishing. http://doi.org/http://doi.org/10.1007/978-3-319-25010-6_7.

Jørgensen, K. A. (2009). Classification of Building Element Functions. In A. Dikbas, E. Ergen, & H. Giritli (Eds.), *26th International Conference on IT in Construction & 1st International Conference on Managing Construction for Tomorrow* (pp. 301–307). Istanbul: CRC Press LLC.

Jørgensen, K. A., & Skauge, J. (2008). *Building Models and Building Modelling*. Aalborg University.

Kadolsky, M., Baumgärtel, K., & Scherer, R. J. (2014). An ontology framework for rule-based inspection of eeBIM-systems. In *Procedia Engineering* (Vol. 85, pp. 293–301). Elsevier Ltd.

Karan, E. P., Irizarry, J., & Haymaker, J. (2015). BIM and GIS integration and interoperability based on semantic web technology. *Journal of Computing in Civil Engineering*, *30*(3), 4015043. http://doi.org/10.1061/(ASCE)CP.1943-5487.0000519.

Karnstedt, M., Sattler, K. U., Geist, I., & Höpfner, H. (2003). Semantic Caching in Ontology-based Mediator Systems. *Berliner XML Tage*, 155–169.

Katranuschkov, P., Gehre, A., & Scherer, R. J. (2003). An ontology framework to access IFC model data. *Electronic Journal of Information Technology in Construction (ITcon)*, *8*, 413–437.

Kerrigan, S., & Law, K. H. (2003). Logic-based regulation compliance-assistance. In *9th international conference on Artificial intelligence and law - ICAIL '03* (pp. 126–135). Scotland. http://doi.org/10.1145/1047788.1047820.

Kestle, L. ., & London, K. (2002). Towards the development of a conceptual design management model for remote sites. *10th Annual Conference on Lean Construction (IGLC)*, 309–322.

Khalfan, M., Khan, H., & Maqsood, T. (2015). Building information model and supply chain integration: A review. *Journal of Economics, Business and Management*, *3*(9), 912–916. http://doi.org/10.7763/JOEBM.2015.V3.308.

Khanzode, M. F., & Reed, D. (2008). Benefits and lessons learned of implementing building virtual design and construction (VDC) technologies for coordination of mechanical, electrical, and plumbing. *Electronic Journal of Information Technology in Construction (ITcon)*, *13*, 324–342.

Kimball, R. (1996). *The data warehouse toolkit: practical techniques for building dimensional data warehouse*. New York: John Wiley & Sons.

Kiviniemi, A., Fischer, M., & Bazjanac, V. (2005). Integration of Multiple Product Models : IFC Model Servers as a Potential Solution. In R. J. Scherer, P. Katranuschkov, & S. E. Schapke (Eds.), *22nd Conference on Information Technology in Construction* (pp. 37–40). Dresden.

Klein, M. (2001). Combining and relating ontologies: an analysis of problems and solutions. *IJCAI-01 Workshop on Ontologies and Information Sharing*, *47*(1), 53–62. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.13.3504&rep=rep1&type=pdf#page=55.

Klyne, G., & Carroll, J. (2004). Resource Description Framework (RDF): Concepts and Abstract Syntax. W3C Recommendation. Retrieved from https://www.w3.org/TR/2004/REC-rdf-concepts-20040210/.

Knopp-Trendafilova, A., Suomi, J., & Tauriainen, M. (2009). Link between a structural model of buildings and classification systems in construction. In *1st International Conference on Improving Construction and Use through Integrated Design*

Solutions, CIB IDS (pp. 285–301). Espoo.

Kolias, V. D., Stoitsis, J., Golemati, S., & Nikita, K. S. (2014). Utilizing Semantic Web Technologies in Healthcare. *Concepts and Trends in Healthcare Information Systems*, *16*, 9–19. http://doi.org/10.1007/978-3-319-06844-2_2.

Koskela, L., Ballard, G., Howell, G., & Tommelein, I. D. (2002). The foundations of lean construction. In R. Best & G. de Valence (Eds.), *Design and Construction: Building in Value* (pp. 211–226). Oxford: Butterworth-Heinemann.

Kotis, K., Vouros, G. A., & Alonso, J. P. (2005). HCOME: A tool-supported methodology for engineering living ontologies. In C. Bussler, V. Tannen, & I. Fundulaki (Eds.), *Semantic Web and Databases. Second International Workshop - SWDB 2004* (Vol. 3372, pp. 155–166). Toronto: Springer Berlin Heidelberg. http://doi.org/10.1007/978-3-540-31839-2_12.

Laat, R. De, & Berlo, L. Van. (2011). Integration of BIM and GIS: The development of the CityGML GeoBIM extension. *Advances in 3D Geo-Information Sciences*, 211–225. http://doi.org/10.1007/978-3-642-12670-3_13.

Laiserin, J. (2002). Comparing Pommes and Naranjas. *The Laiserin Letter*, (15), 1–3.

Laiserin, J. (2003). The BIM page: Building information modeling – the great debate. *The Laiserin Letter*. Retrieved from http://www.laiserin.com/features/bim/index.php.

Lassila, O., & McGuinness, D. (2001). Technological standards, innovation, and essential facilities: Toward a Schumpeterian post-Chicago approach. *Linköping Electronic Articles in Computer and Information Science*, *6*(5), 9. Retrieved from http://www.ep.liu.se/ea/cis/2001/005.

Lassoued, Y., Wright, D., Bermudez, L., & Boucelma, O. (2008). Ontology-based Mediation of OGC Catalogue Service for the Web: A Virtual Solution for Integrating Coastal Web Atlases. In J. Cordeiro, S. Shishkov, A. Ranchordas, & M. Hrlfert (Eds.), *3rd International Conference on Data and Software Engineering ICSOFT* (Vol. 1, pp. 192–197). Berlin: INSTICC Press.

Lee, G., Sacks, R., & Eastman, C. (2006). Specifying parametric building object behavior (BOB) for a building information modeling system. *Automation in Construction*, *15*(6), 758–776. http://doi.org/10.1016/j.autcon.2005.09.009

Li, Y. (2015). *Automated Code-checking of BIM models*. University of Cantabria.

Li, Y., & Wang, S. Q. (2003). A Framework for Evaluating IT Benefits in Construction Companies. In *20th CIB W78 International Conference* (pp. 193–203). Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.540.7818&rep=rep1&type=pdf.

Liebich, T. (1999). Layering concept of IFC architecture.

Liebich, T. (2014). IFC overview presentation. Retrieved from http://www.bre.co.uk/filelibrary/events/BRE Events/BIM Conference Season/Delivery of IFC/2-Thomas-Liebich.pdf.

Liebich, T., & Wix, J. (2000). IFC technical guide, Industry Foundation Classes – Release 2x. International Alliance for Interoperability.

Lima, C., Stephens, J., & Böhms, M. (2003). The BCXML: Supporting ecommerce and knowledge management in the construction industry. *Electronic Journal of*

Information Technology in Construction (ITcon), 8, 293–308. Retrieved from http://www.itcon.org/data/works/att/2003_22.content.08439.pdf.

Lima, C., Zarli, A., & Storer, G. (2007). Controlled vocabularies in the European construction sector: evolution, current developments, and future trends. In *Complex Systems Concurrent Engineering* (pp. 565–574). Springer London.

Lohmann, S., Negru, S., Haag, F., & Ertl, T. (2016). Visualizing Ontologies with VOWL. *Semantic Web, 7*(4), 399–419. http://doi.org/10.3233/SW-150200.

Love, P. E., Irani, Z., & Edwards, D. J. (2005). Researching the investment of information technology in construction: An examination of evaluation practices. *Automation in Construction*, *14*(4), 569–582. http://doi.org/10.1016/j.autcon.2004.12.005

MacLeamy, P. (2004). MacLeamy Curve. Collaboration, Integrated Information, and the Project Lifecycle in Building Design and Construction and Operation (WP-1202).

Maddison, R. (1989). Information systems development for managers. London: Paradigm.

Madrazo, L. (1989). *Using CAD as a tool for designing*. http://doi.org/10.13140/RG.2.1.1686.7045.

Madrazo, L. (1990). The integration of computer modeling in architectural design. In P. Jordan (Ed.), *ACADIA 90. Research and Practice*. University of Montana.

Madrazo, L., Sicilia, Á., González, M., & Martin, A. (2009). Barcode housing system: Integrating floor plan layout generation processes within an open and collaborative system to design and build customized housing. *13th International CAAD Futures Conference*, 656–670.

Mahdjoubi, L., Brebbia, C. A., & Laing, R. (2015). *Building information modelling (BIM) in design, construction and operations* (Vol. 149). WIT Press.

Manola, F., & Miller, E. (2004). RDF Primer, W3C Recommendation. Retrieved from http://www.w3.org/TR/rdf-primer.

Martin, C., & Powell, P. (1992). *Information Systems: A Management Perspective*. McGraw Hill Book Co Ltd.

Martins, J. P. P., Carvalho, B., & Almeida, V. A. (2016). Automated rule-checking – a tool for design development. In *41st IAHS World Congress on Housing - Sustainability and Innovation for the Future*. Albufeira. Retrieved from http://hdl.handle.net/10216/85536.

Matsokis, A., & Kiritsis, D. (2010). An ontology-based approach for Product Lifecycle Management. *Computers in Industry*, *61*(8), 787–797. http://doi.org/10.1016/j.compind.2010.05.007

McGuinness, D. L., & Van Harmelen, F. (2004). OWL web ontology language overview. *World Wide Web Consortium (W3C) Recommendation*, 22. Retrieved from http://www.w3.org/TR/owl-features.

Mingers, J. C. (1995). Information and meaning: foundations for an intersubjective account. *Information Systems Journal*, *5*(4), 285–306. http://doi.org/10.1111/j.1365-2575.1995.tb00100.x

Mitra, P., Noy, N., & Jaiswal, A. (2005). Ontology Mapping Discovery with Uncertainty. In *4th International Semantic Web Conference (ISWC)* (Vol. 3729, pp. 537–547).

Motik, B., Grau, B. C., Horrocks, I., Wu, Z., Fokoue, A., & Lutz, C. (2009). OWL 2 web ontology language: Profiles. *World Wide Web Consortium (W3C) Editor's Draft*, 53. Retrieved from https://www.w3.org/2007/OWL/draft/ED-owl2-profiles-20090420/all.pdf.

Mowrer, F. W. (1994). *Development of the fire data management system*. Gaithersburg: US Department of Commerce, National Institute of Standards and Technology,. Retrieved from http://www.fire.nist.gov/bfrlpubs/fire94/PDF/f94029.pdf.

Nawari, N. O., & Alsaffar, A. (2015). Understanding Computable Building Codes. *Civil Engineering and Architecture*, *3*(6), 163–171. http://doi.org/10.13189/cea.2015.030601.

Nolle, A., Nemirovski, G., & Sicilia, A. (2013). *Deliverable 4.5 Semantic Energy Information Framework*. Technical report, ICT 287534. Retrieved from http://www.semanco-project.eu/index_htm_files/SEMANCO_D4.5_20131018.pdf.

Noy, N. F. (2004). Semantic integration: a survey of ontology-based approaches. *SIGMOD Record*, *33*(4), 65–70. Retrieved from citeulike-article-id:86456%5Cnhttp://dx.doi.org/10.1145/1041410.1041421.

Noy, N. F., & McGuinness, D. L. (2001). *Ontology development 101: A guide to creating your first ontology, Technical Report SMI-2001-0880*.

O'Brien, P., & Cui, Z. (2000). Domain Ontology Management Environment. *33rd Annual Hawaii International Conference on System Sciences*, *0*, 1–9. http://doi.org/10.1109/HICSS.2000.926977.

O'Connor, M. J., Shankar, R., Nyulas, C., Tu, S., & Das, A. (2008). Developing a web-based application using OWL and SWRL. In *AAAI spring symposium: AI meets business rules and process management* (pp. 93–98). Stanford. Retrieved from http://www.aaai.org/Papers/Symposia/Spring/2008/SS-08-01/SS08-01-012.pdf.

O'Donnell, J., Corry, E., Hasan, S., Keane, M., & Curry, E. (2013). Building performance optimization using cross-domain scenario modeling, Linked data, And complex event processing. *Building and Environment*, *62*, 102–111.

O'Donnell, J., See, R., Rose, C., Maile, T., Bazjanac, V., & Haves, P. (2011). SimModel: A domain data model for whole building energy simulation. In *12th Conference of International Building Performance Simulation Association* (pp. 382–389). Sydney. Retrieved from http://escholarship.org/uc/item/70c7j74t.

Obitko, M. (2007). *Translations between ontologies in multi-agent systems*. Czech Technical University.

Ogunkah, I. C. B., & Yang, J. (2013). A Decision Support System for the Selection of Low-Cost Green Building Materials. *Journal of Scientific Research & Reports*, *3*(1), 17–96. http://doi.org/10.9734/JSRR/2014/5892.

Onyegiri, I., Nwachukwu, C., & Jamike, O. (2011). Information and communication technology in the construction industry. *American Journal of Scientific and Industrial Research*, *2*(3), 461–468. http://doi.org/10.5251/ajsir.2011.2.3.461.468.

Paterson, G., Harty, J., & Kouider, T. (2016). *Getting to Grips with BIM: A Guide for Small and Medium-sized Architecture, Engineering and Construction Firms*. Routledge.

Patil, L., Dutta, D., & Sriram, R. (2005). Ontology-based exchange of product data semantics. *IEEE Transactions on Automation Science and Engineering*, *2*(3), 213–225.

Paulson, B. (1976). Designing to Reduce Construction Costs. *ASCE Journal of the Construction Division, Now Called, Journal of Construction Engineering and Management*, *102*(4), 587–592. Retrieved from http://cedb.asce.org/cgi/WWWdisplay.cgi?7078.

Pauwels, P. (2012). *Reconsidering information system support for architectural design thinking*. Ghent University.

Pauwels, P. (2014). *Supporting Decision-Making in the Building Life-Cycle Using Linked Building Data*. *Buildings* (Vol. 4). http://doi.org/10.3390/buildings4030549.

Pauwels, P., Corry, E., & O'Donnell, J. (2014). Representing SimModel in the web ontology language. *American Society of Civil Engineers*, 2271–2278. http://doi.org/http://dx.doi.org/10.1061/9780784413616.282.

Pauwels, P., & Terkaj, W. (2016). EXPRESS to OWL for construction industry: Towards a recommendable and usable ifcOWL ontology. *Automation in Construction*, *63*, 100–133. http://doi.org/10.1016/j.autcon.2015.12.003

Pauwels, P., Van Deursen, D., Verstraeten, R., De Roo, J., De Meyer, R., Van De Walle, R., & Van Campenhout, J. (2011). A semantic rule checking environment for building performance checking. *Automation in Construction*, *20*(5), 506–518. http://doi.org/10.1016/j.autcon.2010.11.017

Pauwels, P., & Zhang, S. (2015). Semantic rule-checking for regulation compliance checking: an overview of strategies and approaches. In J. Beetz, L. Berlo, T. Hartmann, & R. Amor (Eds.), *32th CIB W78 International Conference* (pp. 619–628). Eindoven.

Peansupap, V., & Walker, D. (2005). Factors enabling information and communication technology diffusion and actual implementation in construction organisations. *Electronic Journal of Information Technology in Construction (ITcon)*, *10*(1), 193–218. Retrieved from http://www.itcon.org/2005/14.

Pedrinaci, C., & Domingue, J. (2009). Ontology-based metrics computation for business process analysis. In *4th International Workshop on Semantic Business Process Management* (pp. 43–50). ACM Press. http://doi.org/10.1145/1944968.1944976.

Penttilä, H. (2006). Describing the changes in architectural information technology to understand design complexity and free-form architectural expression. *Electronic Journal of Information Technology in Construction (ITcon)*, *11*, 395–408. Retrieved from http://www.itcon.org/cgi-bin/works/Show?2006_29.

Perez, A., Larrinaga, F., & Curry, E. (2013). The Role of Linked Data and Semantic-Technologies for Sustainability Idea Management. In *Software Engineering and Formal Methods (SEFM)* (pp. 306–312). Springer International Publishing. http://doi.org/10.1007/978-3-319-05032-4_22.

Pinkel, C., Binnig2, C., Enez-Ruiz, E., May, W., Ritze, D., Skjæveland, M. G., … Kharlamov, E. (2015). RODI: A Benchmark for Automatic Mapping Generation in Relational-to-Ontology Data Integration. In *12th European Semantic Web Conference, ESWC 2015* (pp. 21–37). Portoroz: Springer International Publishing. http://doi.org/http://doi.org/10.1007/978-3-319-18818-8_2.

Pinto, H. S., Staab, S., & Tempich, C. (2004). DILIGENT: Towards a fine-grained methodology for distributed, loosely-controlled and evolving engingeering of ontologies. In R. L. de Mantaras & L. Saitta (Eds.), *16Th European Conference on Artificial Intelligence (ECAI)* (pp. 393–397). Valencia: IOS Press.

Polanyi, M. (1966). *The Tacit Dimenions*. (Garden City, Ed.). New York.

Popowich, F. (2005). Using text mining and natural language processing for health care claims processing. *ACM SIGKDD Explorations Newsletter*, *7*(1), 59–66. http://doi.org/10.1145/1089815.1089824.

Poveda-Villalón, M. (2016). *Ontology Evaluation: a pitfall-based approach to ontology diagnosis*. Polytechnic University of Madrid. Retrieved from http://oops.linkeddata.es.

Preidela, C., & Borrmanna, A. (2015). Automated Code Compliance Checking Based on a Visual Language and Building Information Modeling. In *International Symposium on Automation and Robotics in Construction (ISARC)*. Oulu. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.702.891.

Prud'hommeaux, E., & Lee, R. (2004). W3C RDF validation service. Retrieved from https://www.w3.org/RDF/Validator.

Prud'hommeaux, E., & Seaborne, A. (2008). SPARQL Query Language for RDF. *W3C Recommendation*. Retrieved from http://www.w3.org/TR/rdf-sparql-query.

Radinger, A., Rodriguez-Castro, B., Stolz, A., & Hepp, M. (2013). BauDataWeb: The Austrian Building and Construction Materials Market as Linked Data. In *9th International Conference on Semantic Systems* (pp. 25–32). Graz: ACM. http://doi.org/10.1145/2506182.2506186

Ramaji, I. J., & Memari, A. M. (2016). Interpreted Information Exchange: Systematic Approach for BIM to Engineering Analysis Information Transformations. *Journal of Computing in Civil Engineering*. http://doi.org/10.1061/(ASCE)CP.1943-5487.0000591.

Rattanasawad, T., Saikaew, K. R., Buranarach, M., & Supnithi, T. (2013). A review and comparison of rule languages and rule-based inference engines for the Semantic Web. In *2013 International Computer Science and Engineering Conference (ICSEC)* (pp. 1–6). IEEE. http://doi.org/10.1109/ICSEC.2013.6694743.

Rijgersberg, H., van Assem, M., & Top, J. (2013). Ontology of Units of Measure and Related Concepts. *Semantic Web Journal*, *4*(1), 3–13. Retrieved from http://www.wurvoc.org/vocabularies/om-1.8.

Root, D., & Thorpe, T. (2001). Refocusing collaboration technologies in the construction supply chain: looking beyond the organization. In *ARCOM 17th Annual Conference* (Vol. 1, pp. 253–262). Manchester: University of Salford.

Sack, H. (2013). Lecture 1: The Web of Data. Hasso Plattner Institute for IT Systems Engineering, University of Potsdam.

Saluja, C. (2009). *A process mapping procedure for planning building information modeling (BIM) execution on a building construction project*. Pennsylvania State University.

Sanchez, R. (2004). *"Tacit Knowledge" versus "Explicit Knowledge" Approaches to Knowledge Management Practice* (Working Paper Series No. 2004–1). *Department* *of Industrial Economics and Strategy, Copenhagen Business School*. Frederiksberg.

Schevers, H., & Drogemuller, R. (2006). Converting the industry foundation classes to the web ontology language. In *First International Conference on Semantics, Knowledge and Grid (SKG'05)* (pp. 556–560). Washington, DC: IEEE Computer Society. http://doi.org/10.1109/SKG.2005.59.

See, R., Karlshoej, J., & Daves, D. (2011). *An Integrated Process for Delivering IFC Based Data Exchange*. Retrieved from http://www.standard.no/Global/PDF/ISO-TC59-SC13/N_287_Integrated_IDM-MVD_Process_for_IFC-formats.pdf.

SEMANCO. (n.d.). SEMANCO: Semantic tools for carbon reduction in urban planning. Retrieved from http://www.semanco-project.eu/.

Semenov, V. A., Gonahchan, I., Morozov, S. V., & Tarlapan, O. A. (2014). Ontology model for intelligent catalogues of building elements. In *10th European Conference on Product & Process Modelling (ECPPM)* (pp. 527–534). Vienna.

Semenov, V., & Tarlapan, O. (2014). D11.1 Technical Specification of the Ontology for Prefabricated Building Elements Representation. Intelligent services for Energy-Efficient Design and Life Cycle Simulation (ISES) Project No. 288819.

Senescu, R. R., Aranda-Mena, G., & Haymaker, J. (2013). Relationships between Project Complexity and Communication. *Journal of Management in Engineering*, *29*(2), 183–197. http://doi.org/10.1061/(ASCE)ME.1943-5479.0000121.

Seng, L. C. (2012). Singapore BIM guide.

Seo, T. S., Lee, Y., Cheon, S. U., Han, S., Patil, L., & Dutta, D. (2005). Sharing CAD models based on feature ontology of commands history. *International Journal of CAD/CAM*, *5*(1), 39–48.

Shannon, C. E. (1948). The mathematical theory of communication. *The Bell System and Technical Journal*, *27*, 379–423.

Shayeganfar, F., Mahdavi, A., Suter, G., & Anjomshoaa, A. (2008). Implementation of an IFD library using semantic web technologies: A case study. In A. S. Zarli & R. Scherer (Eds.), *7th European Conference on Product & Process Modelling (ECPPM) - eWork and eBusiness in architecture, Engineering and Construction* (pp. 539–544). Sophia.

Sheth, A. (1999). Changing Focus on Interoperability in Information Systems: From System, Syntax, Structure to Semantics. In M. Goodchild, M. Egenhofer, R. Fegeas, & C. Kottman (Eds.), *Interoperating Geographic Information Systems* (pp. 165–180). Norwell, MA: Kluwer Academic Publishers. http://doi.org/10.1007/978-1-4615-5189-8.

Shvaiko, P., & Euzenat, J. (2013). Ontology Matching: State of the Art and Future Challenges. *IEEE Transactions on Knowledge and Data Engineering*, *25*(1), 158–176. http://doi.org/10.1109/TKDE.2011.253.

Sicilia, Á., Costa, G., Corrado, V., & Gorrino, A. (2015). A Semantic Decision Support System to optimize the energy use of public buildings. In J. Beetz, L. Berlo, T. Hartmann, & R. Amor (Eds.), *32rd international CIB W78 conference* (pp. 676–685). Eindhoven: Eindhoven University of Technology.

Sicilia, Á., & Nemirovski, G. (2016). AutoMap4OBDA: Automated Generation of R2RML Mappings for OBDA. In *Knowledge Engineering and Knowledge*

Management: 20th International Conference, EKAW 2016 (pp. 577–592). Bologna: Springer International Publishing. http://doi.org/http://doi.org/10.1007/978-3-319-49004-5_37.

Sicilia, Á., Nemirovski, G., & Nolle, A. (2016). Map-On: A web-based editor for visual ontology mapping. *Semantic Web*, *Preprint*, 1–12. http://doi.org/10.3233/SW-160246.

Sidawi, B. (2012). The Impact of Social Interaction and Communications on Innovation in the Architectural Design Studio. *Buildings*, *2*(3), 203–217. http://doi.org/10.3390/buildings2030203

Smart, P. (2007). *Rule-Based Intelligence on the Semantic Web: Implications for Military Capabilities*. Southampton: Technical Report.

Solihin, W., & Eastman, C. (2015). Classification of rules for automated BIM rule checking development. *Automation in Construction*, *53*, 69–82. http://doi.org/10.1016/j.autcon.2015.03.003

Sowa, J. F. (1999). *Knowledge Representation: Logical, Philosophical, and Computational Foundations*.

Stavric, M., & Marina, O. (2011). Parametric Modeling for Advanced Architecture. *International Journal of Applied Mathematics and Informatics*, *5*(1), 9–16.

Steel, J., Drogemuller, R., & Toth, B. (2012). Model interoperability in building information modelling. *Software and Systems Modeling*, *11*(1), 99–109. http://doi.org/10.1007/s10270-010-0178-4.

Stenmark, D. (2001). The Relationship between Information and Knowledge. In *24th Information Systems Research Seminar in Scandinavia (IRIS)* (Vol. 24, pp. 11–14). Ulvik.

Stroka, S. (2005). *Knowledge Representation Technologies in the Semantic Web*. *Information Technology and System Management*. Salzburg.

Succar, B. (2009). Building information modelling maturity matrix. In J. Underwood & U. Isikdag (Eds.), *Handbook of research on building information modelling and construction informatics: Concepts and technologies* (pp. 65–103). Information Science Reference, IGI Publishing. http://doi.org/10.4018/978-1-60566-928-1.ch004.

Succar, B. (2010). The five components of BIM performance measurement. In *18th CIB World Building Congress (combined with W104)*. Salford.

Tah, J. H. M., & Abanda, H. F. (2011). Sustainable building technology knowledge representation: Using Semantic Web techniques. *Advanced Engineering Informatics*, *25*(3), 547–558. http://doi.org/10.1016/j.aei.2011.02.006.

Terkaj, W., & Pauwels, P. (2015). OWL ontology file for the IFC4 ADD1.exp EXPRESS schema. Retrieved from http://linkedbuildingdata.net/resources/20150824_IFC4_ADD1.owl.

The Apache Software Foundation. (2015). Apache Jena. Retrieved from http://jena.apache.org.

Thierauf, R. J. (1999). *Knowledge management systems for business*. Quorum Books, Westport, CT.

Thomassen, M. (2011). *BIM & Collaboration in the AEC Industry*. *Construction Management, Master's (MSc)*. Aalborg University.

Tolman, F. P., & Böhms, H. M. (2002). Electronic business in the buildingconstruction industry: preparing for the new Internet. *Construction Information Technology*, *2*, 928–936.

Trinh, Q., Barker, K., & Alhajj, R. (2006). RDB2ONT: A Tool for Generating OWL Ontologies From Relational Database Systems. *Advanced Int'l Conference on Telecommunications and Int'l Conference on Internet and Web Applications and Services (AICT-ICIW)*. http://doi.org/10.1109/AICT-ICIW.2006.159.

UK Cabinet Office. (2016). Government Construction Strategy 2016-20. Retrieved from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/510354/Government_Construction_Strategy_2016-20.pdf.

Ullman, J. (1997). Information integration using logical views. In *6th International Conference on Database Theory (ICDT)* (Vol. 1186, pp. 19–40). Delphi: Springer Berlin Heidelberg. http://doi.org/10.1007/3-540-62222-5_34.

Uschold, M. (2000). Creating, integrating and maintaining local and global ontologies. In *14th European Conference on Artificial Intelligence*. Berlin.

Van Berlo, L. A. H. M., & Bomhof, F. (2014). Creating the Dutch national BIM levels of development. In *American Society of Civil Engineers (ASCE)* (pp. 129–136). Orlando. http://doi.org/10.1061/9780784413616.017.

Van Nederveen, G. A., & Tolman, F. P. (1992). Modelling multiple views on buildings. *Automation in Construction*, *1*(3), 215–224. http://doi.org/10.1016/0926-5805(92)90014-B.

Vatant, B., & Wick., M. (2012). GeoNames ontology. Retrieved from http://www.geonames.org/ontology/.

Vavliakis, K. N., Grollios, T. K., & Mitkas, P. A. (2010). Rdote - transforming relational databases into semantic web data. In *2010 International Conference on Posters & Demonstrations Track* (Vol. 658, pp. 121–124). CEUR-WS.

Veltman, K. H. (2001). Syntactic and semantic interoperability: new approaches to knowledge and the semantic web. *New Review of Information Networking*, *7*(1), 159–183. http://doi.org/10.1080/13614570109516975.

W3C OWL Working Group. (2009). OWL 2 Web Ontology Language Document Overview. Retrieved from https://www.w3.org/TR/2009/WD-owl2-overview-20090327/.

W3C OWL Working Group. (2012). OWL 2 Web Ontology Language Document Overview (Second Edition). W3C Recommendation. Retrieved from http://www.w3.org/TR/owl2-overview/.

Wache, H., Voegele, T., Visser, U., Stuckenschmidt, H., Schuster, G., Neumann, H., & Hübner, S. (2001). Ontology-based integration of information-a survey of existing approaches. *IJCAI-01 Workshop: Ontologies and Information Sharing*, *2001*, 108–117.

Wang, H., & Hamilton, A. (2009). BIM integration with geospatial information within the urban built environment. In J. Underwood & U. Isikdag (Eds.), *Handbook of Research on Building Information Modeling and Construction Informatics:*

Concepts and Technologies (pp. 382–404). IGI global.

Weise, M., Liebich, T., Nisbet, N., & Benghi, C. (2016). IFC model checking based on mvdXML. In R. Christodoulou, S. Scherer (Ed.), *11th European Conference on Product & Process Modelling (ECPPM)*. Limassol: CRC press.

Weise, M., Liebich, T., Tulke, J., & Bonsma, P. (2009). *IFC support for model-based scheduling* (InPro Project IP 026716-2).

Weygant, R. S. (2011). *BIM content development: standards, strategies, and best practices*. John Wiley & Sons.

Wiederhold, G. (1992). Mediators in the architecture of future information systems. *IEEE Computer*, *25*(3), 38–49.

Wix, J. (2007). *Information Delivery Manual: Guide to Components and Development Methods*. buildingSMART Norway.

Wix, J. (2008). BIM Automated Code Checking Based on SMARTcodes. In *buildingSMART Forum 2008*. Seoul.

Woestenenk, K. (1998). *A Common Construction Vocabulary*. *Technical report, STABU Foundation*. Ede.

Woestenenk, K. (2000). The LexiCon: an update. In R. Goncalves, A. Steiger-Garcao, & R. Scherer (Eds.), *Product and Process Modelling in Building and Construction - 3th European Conference on Product & Process Modelling (ECPPM)* (pp. 263–266). Balkema.

Woestenenk, K. (2002). The LexiCon: structuring semantics. In *CIB W78 conference on Distributing Knowledge in Building 2002* (Vol. 2, pp. 241–247). Aarhus.

Woodbury, R., Williamson, S., & Beesley, P. (2006). Parametric Modelling as a Design Representation in Architecture: A Process Account. In *3rd CDEN/RCCI International Design Conference on Education, Innovation, and Practice in Engineering Design* (pp. 158–165). Toronto.

Yang, J., Ahuja, V., & Shankar, R. (2007). Managing Building Projects through Enhanced Communication-An ICT Based Strategy for Small and Medium Enterprises. In R. Milford (Ed.), *CIB World Building Conference 2007*. Cape Town.

Zakaria, Z., Mohamed Ali, N., Tarmizi Haron, A., Marshall-Ponting, J., & Abd Hamid, Z. (2013). Exploring the adoption of Building Information Modelling (BIM) in the Malaysian construction industry: A qualitative approach. *IJERT: International Journal of Research in Engineering and Technology*, *2*(8), 384–395. http://doi.org/10.1017/CBO9781107415324.004.

Zhang, J., & El-Gohary, N. (2012). Automated regulatory information extraction from building codes leveraging syntactic and semantic information. In *ASCE Construction Research Congress* (pp. 622–632). West Lafayette. http://doi.org/10.1061/9780784412329.063.

Zhang, S., Teizer, J., Lee, J. K., Eastman, C. M., & Venugopal, M. (2013). Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules. *Automation in Construction*, *29*, 183–195. http://doi.org/10.1016/j.autcon.2012.05.006.

8

Appendix

8.1. Survey on the penetration of BIM in the AEC industry in Spain

The survey was conducted between January 26th and February 16th, 2016, in collaboration with the BIM user community in Catalonia. A total of 124 practitioners participated. Personal networks of contacts of the members of this group, and social networks, have been the main dissemination channel to invite professions to participate in the survey and to communicate its results.

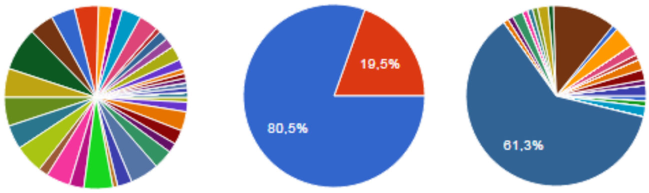
The survey was mainly focused on evaluating the knowledge of professionals of the AEC industry in Spain regarding three topics: interoperability, integrated practice in architecture and BIM. The purpose of the survey was to find out how the industry is currently working and to contribute to making professionals involved in this survey more aware of the existing methodologies, technologies and standards to carry out their professional work more efficiently.

The survey was organized into eleven thematic blocks:

1. Profile and professional roles
2. Software
3. BIM
4. Training in BIM
5. Terminology and concepts
6. Interoperability
7. Collaborative work
8. Data and model
9. Components and products
10. Checking
11. BIM delivery documents

8.1.1. Profile and professional roles

Age | **Gender** | **Location**

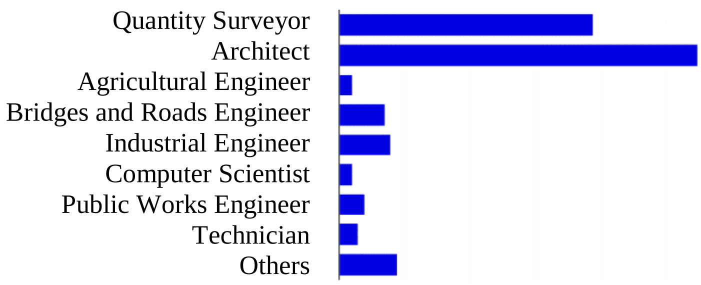


24 and 70 years

Men (80.5%)
Women (19.5%)

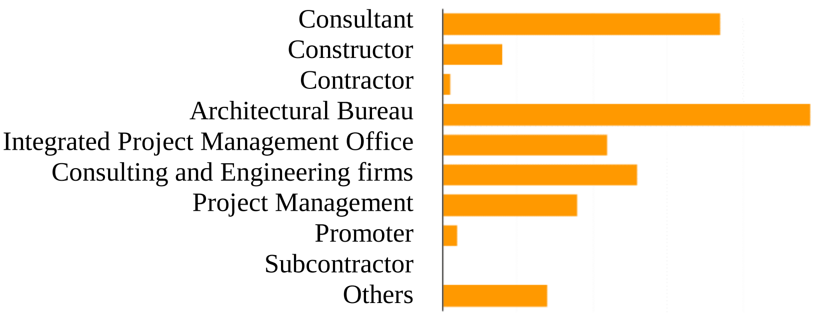
La Coruña:	0.9%
Alicante:	0.9%
Asturias:	1.9%
Barcelona:	61.3%
Castellón:	0.9%
Córdoba:	0.9%
Cuenca:	1.9%
Huesca:	0.9%
Las Palmas:	0.9%
León:	0.9%
Lérida:	1.9%
Lugo:	0.9%
Madrid:	11.3%
Málaga:	0.9%
Navarra:	3.8%
Salamanca:	1.9%
Sevilla:	0.9%
Valencia:	1.9%
Valladolid:	1.9%
Vizcaya:	0.9%
Foreigner:	1.9%

Professional profile *(*multiple choice question)*



*others: civil engineer, mechanical engineer.

Company profile *(*multiple choice question)*

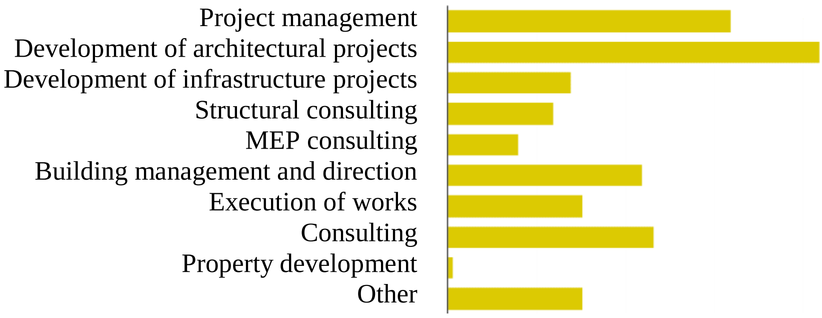


*others: University, research institute, software distributor, prefabricated company, administration and services.

Professional role *(*multiple choice question)*

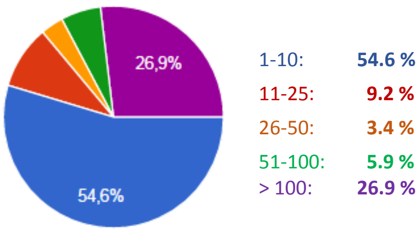
*others: CAD manager, deputy manager, BIM technician, project manager, no profession.

Company activity *(*multiple choice question)*

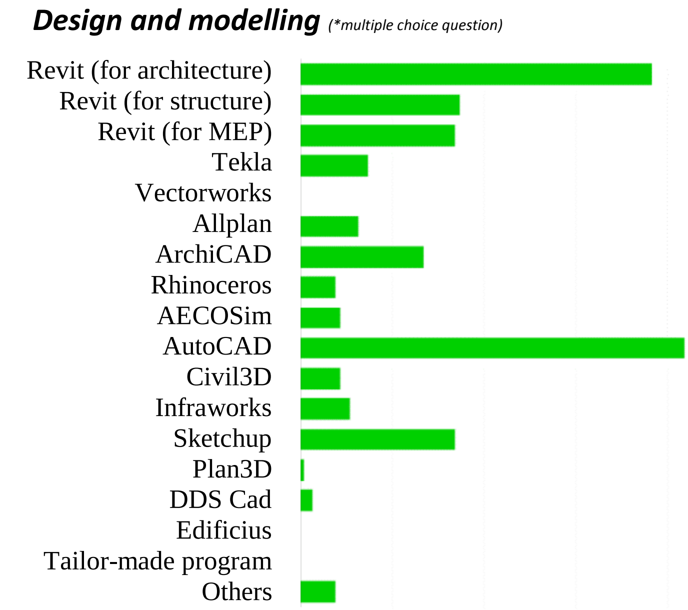


*others: outsourcing BIM, managing contracting, design management, detail engineering, teaching

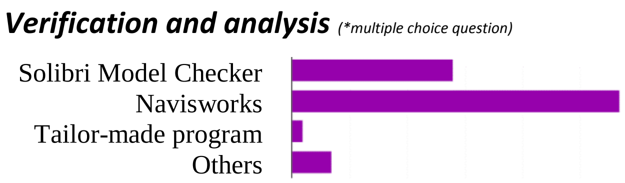
Company size



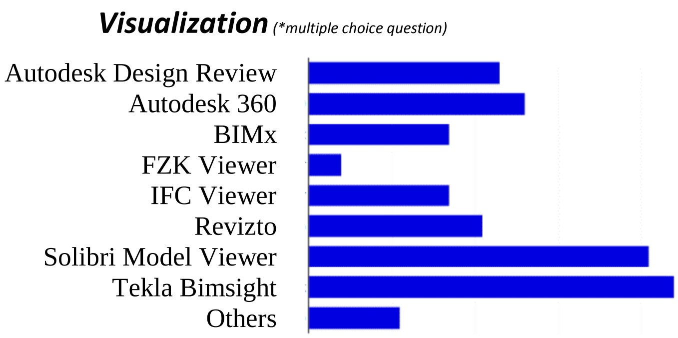
8.1.2. Software



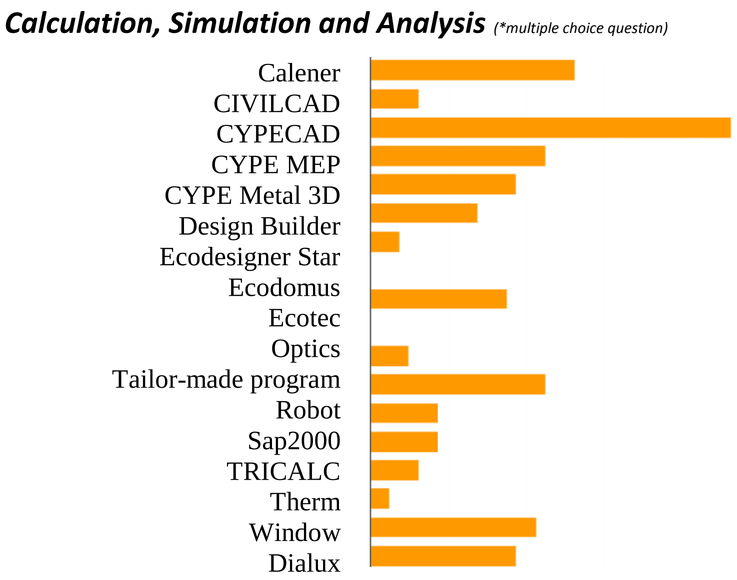
*others: Intellicad, Microstation, Tricad MS, Inventor, Cype



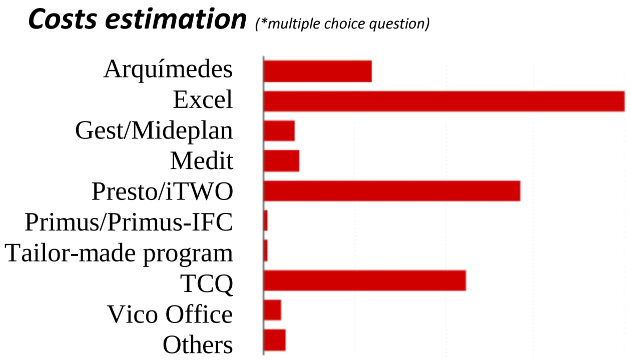
*others: Tekla BIM sight, Simple BIM, Synchro, BIMPlus



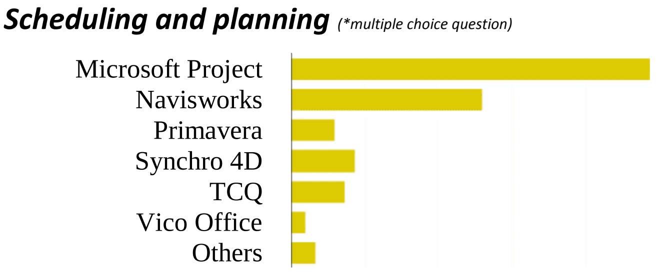
*others: BIM vision, Autodesk Design Review, Revit, Navisworks



*others: TCQ GMA, OpenStudio, Phpp, ETABS, Cerma, dRofus, Scia, Staad pro (Bentley), Metalpla

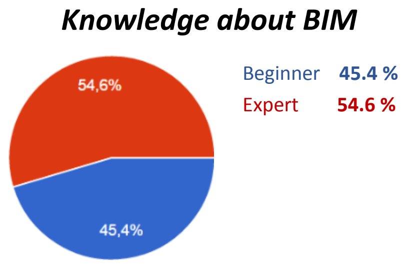


*others: Navision, COSTOS S10, g-prog

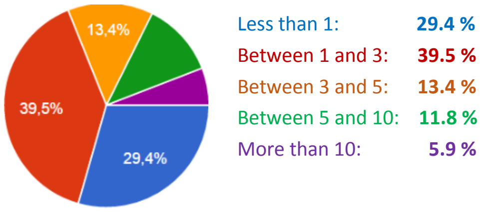


*others: Geniebelt, Excel, Lean Construction, Cype Control de Obra

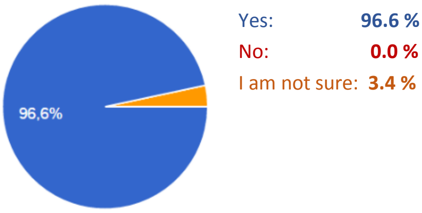
8.1.3. BIM



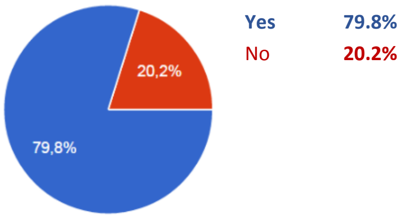
Years working with BIM



Is BIM here to stay?

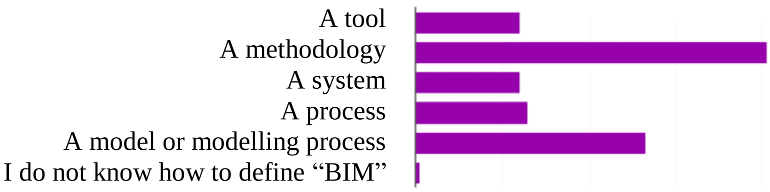


Participation in BIM projects

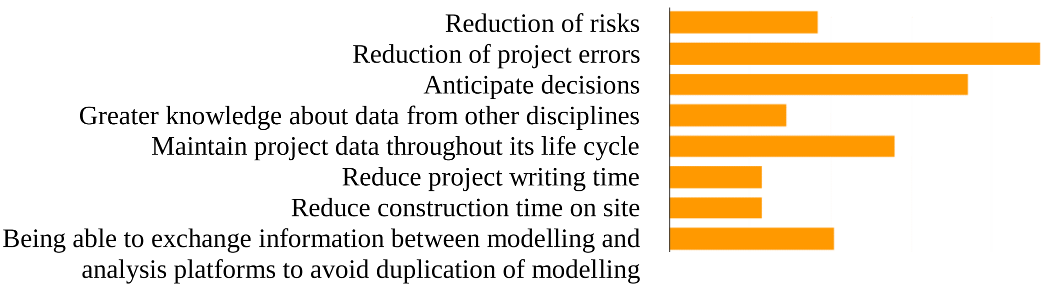


Type of participation in BIM projects *(*multiple choice question)*

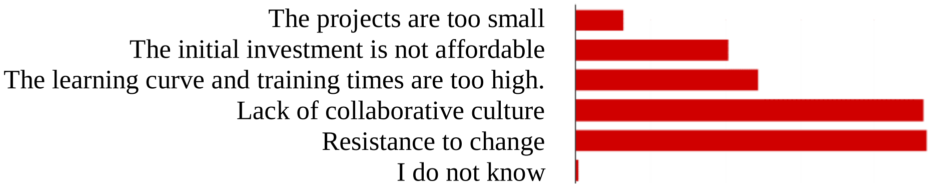
What is BIM? *(*multiple choice question)*



The 3 most relevant expectations in the use of BIM *(*multiple choice question)*

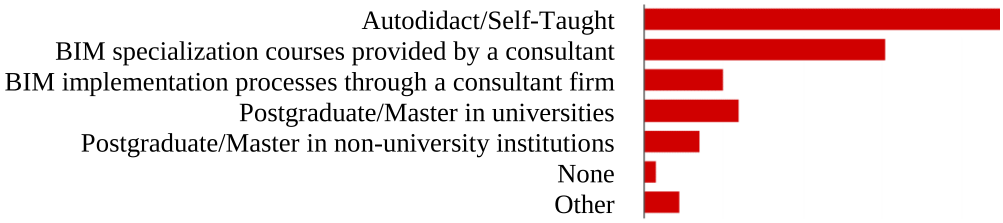


What are the 3 main barriers to using BIM? *(*multiple choice question)*

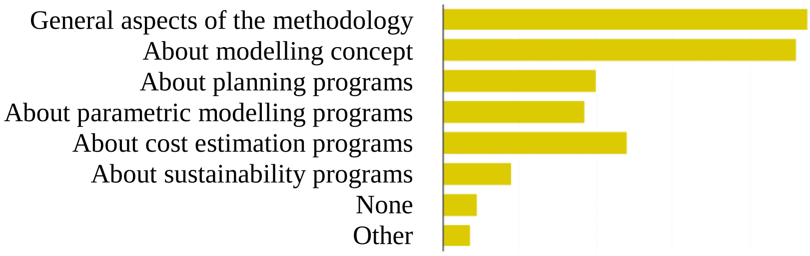


8.1.4. Training in BIM

How did you learn BIM? *(*multiple choice question)*

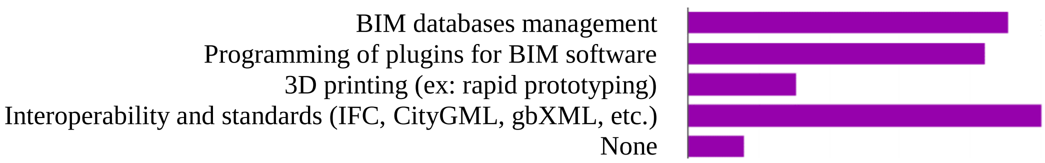


What kind of training in BIM have you received? *(*multiple choice question)*



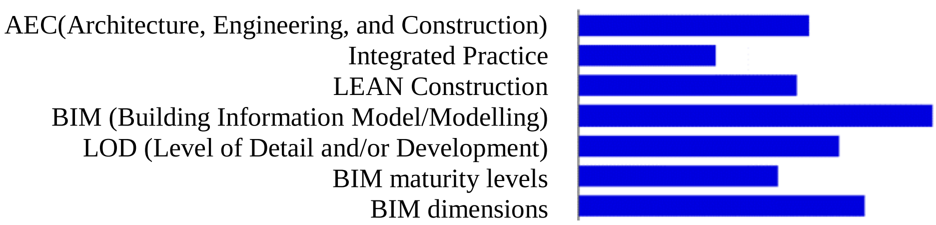
How did you receive the training? *(*multiple choice question)*

What training would you like to receive that is currently not taught? *(*multiple choice question)*

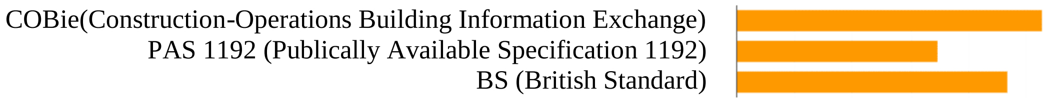


8.1.5. Terminology and concepts

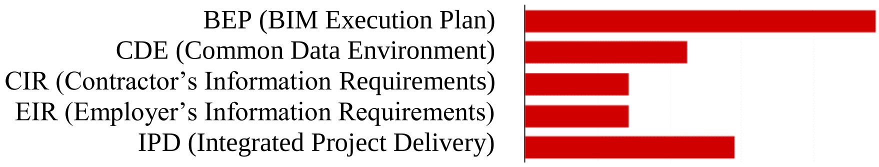
Select the BIM-related concepts you are familiar with *(*multiple choice question)*



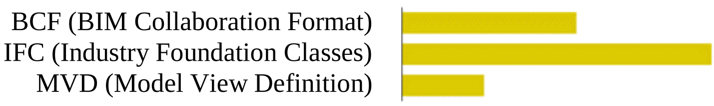
International standards and specifications you are familiar with *(*multiple choice question)*



Planning, development and delivery of projects you are familiar with *(*multiple choice question)*

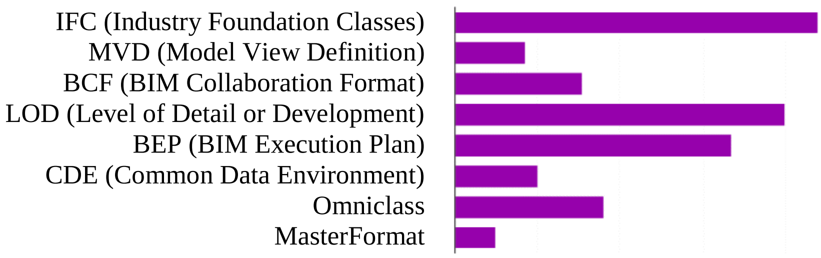


Interoperability and standardization you are familiar with *(*multiple choice question)*



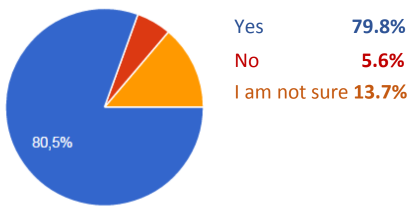
Classification systems you are familiar with *(*multiple choice question)*

Which of the following concepts have you ever applied in your projects? *(*mult. cho. question)*



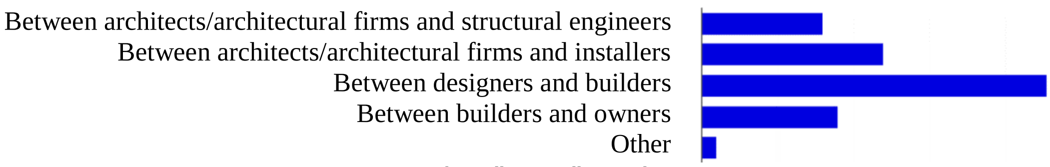
Do you agree with the following definitions of BIM dimensions?

- 2D: 2D representation
- 3D: 3D representation
- 4D: Planning
- 5D: Cost estimate
- 6D: Performance and sustainability
- 7D: Maintenance management



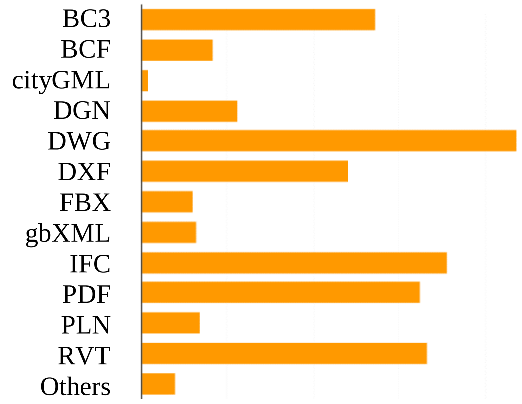
8.1.6. Interoperability

What is the most critical information exchange scenario? *(*multiple choice question)*



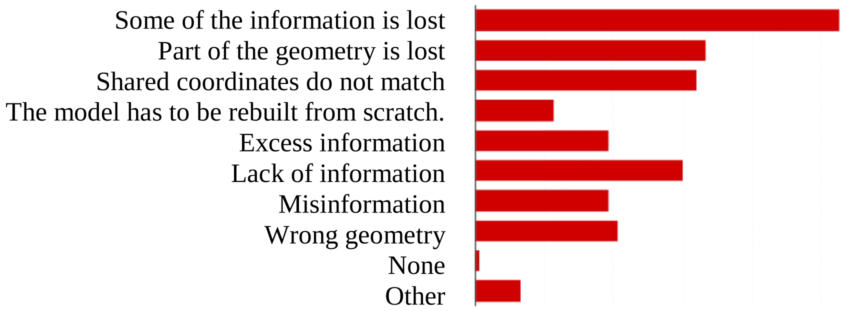
*others: all are equally critical

Exchange formats used in the projects in which you have participated *(*multiple choice question)*



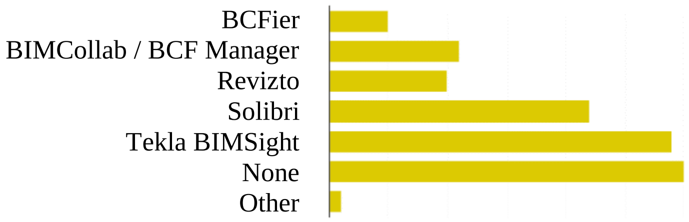
*others: .NWD, .NWF, .NWC, .SMC, .3DS, .obj

Problems and errors experienced in the exchange of information *(*multiple choice question)*



*others: lack of feedback; information in models with different levels of definition; lack of discretization of elements; elements duplicated in the models produced in different disciplines lead to inconsistencies; lack of a universal exchange format that enables to take full advantage of the work done in the different disciplines involved in a project; lack of knowledge of the data structure of BIM models.

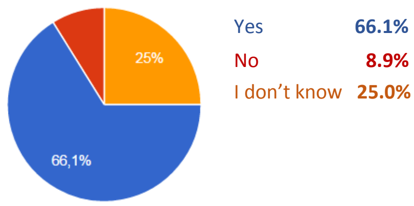
What BCF manager do you currently use? *(*multiple choice question)*



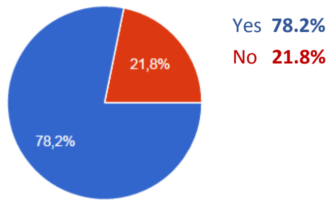
*others: Navisworks

Do you agree with the definition of the LOD levels?

LOD 100: elements are conceptual models and can be represented graphically through a symbol or other generic representation.
LOD 200: may include more accurate graphic information of elements represented as objects or systems with approximate size, shape, location and orientation; and non-graphical information.
LOD 300: adds to the elements defined in LOD 200 information about the size, shape, location, and orientation.
LOD 350: adds information about interfaces with other building systems to the LOD 300.
LOD 400: this level adds to the LOD 350 detailed information about detailing, manufacturing, assembly and installation.
LOD 500: defines element information in "as-built" and "field-verified" terms.

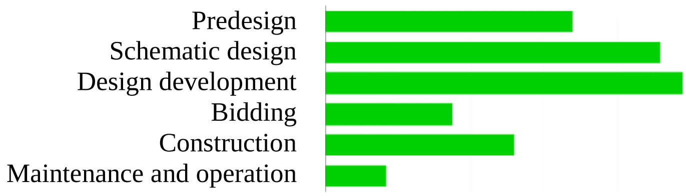


Participation in BIM projects

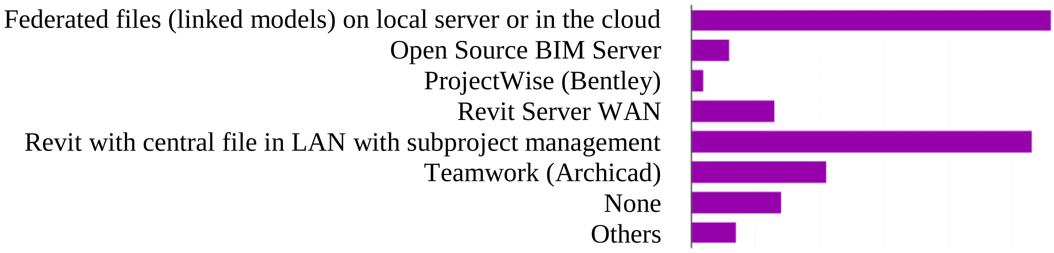


8.1.7. Collaborative work

Stages in which BIM is usually used in projects *(*multiple choice question)*

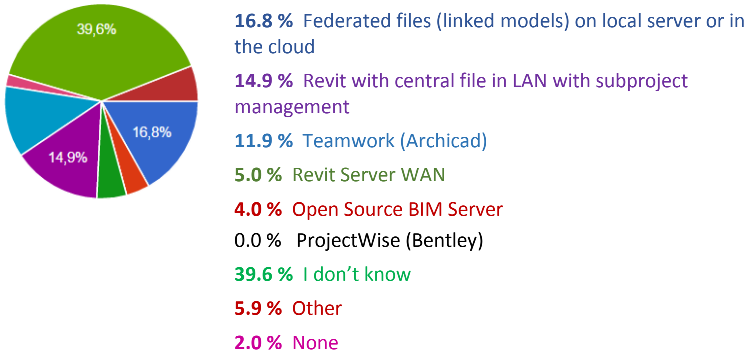


Type of distributed BIM platforms *(*multiple choice question)*

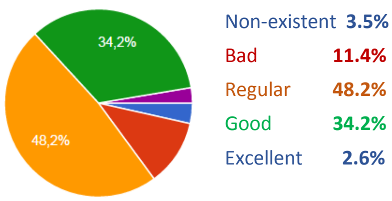


*others: BIM BOX, Aconex

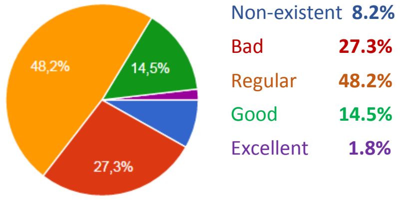
More efficient BIM platforms



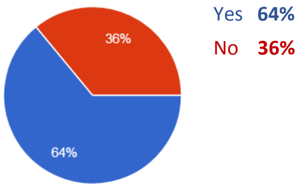
Communication between agents in the design development stage



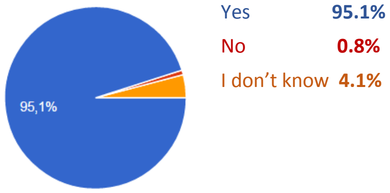
Communication between agents in the construction stage



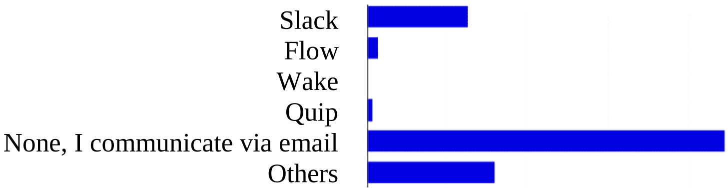
Do you use any documents to regulate the functions, responsibilities, contents, and/or requirements and the information to be exchanged in projects?



Is the BIM a vector of change in the overall improvement of efficiency in the AEC industry?

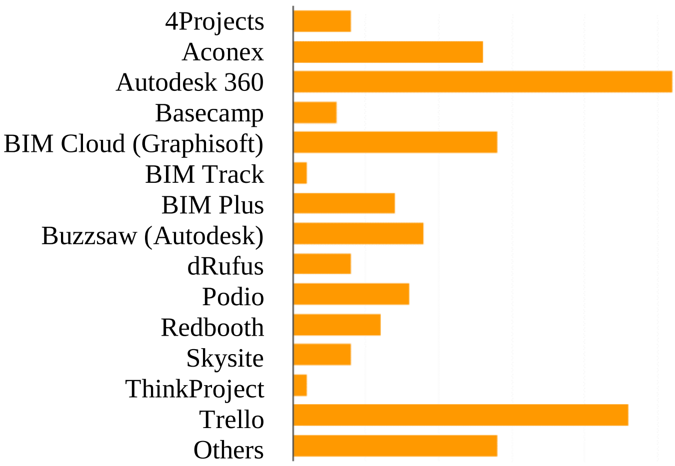


Comprehensive communication tools and platforms *(*multiple choice question)*



*others: Assana, GoToMeeting, Wunderlist, Conject, Skype, Teamviewer, In Touch, Podio, Aconex, linking files in BIM BOX, PROJECT Center.

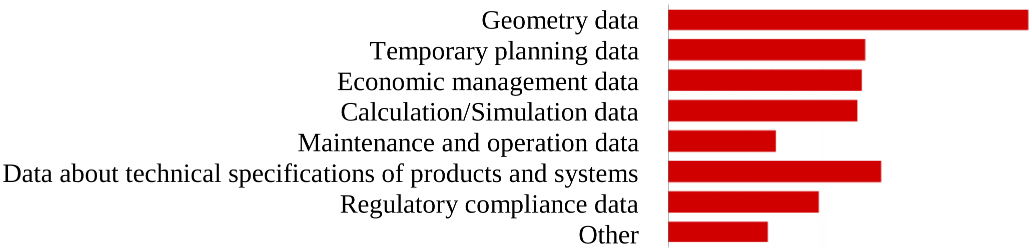
Collaborative project management tools *(*multiple choice question)*



*others: Wunderlist, Intouch, BIM6D, Asana, Gestproject, PROJECT Center, eDOC, Omnifocus

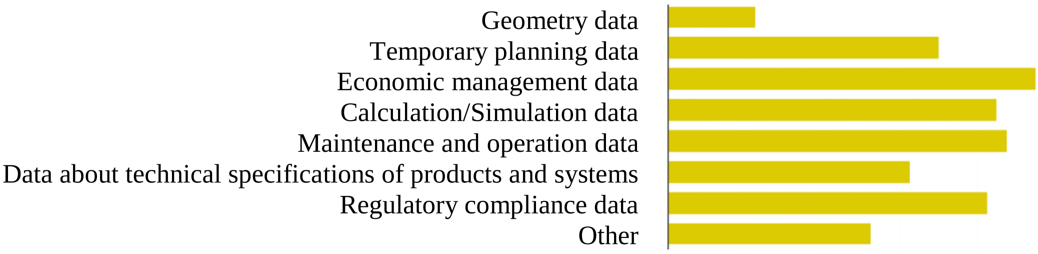
8.1.8. Data and model

Required data from other agents *(*multiple choice question)*



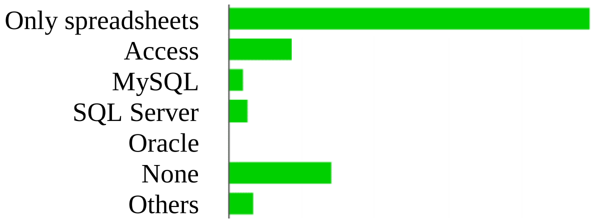
*others: Prices, measurements and others that have not been specified

More problematic data to integrate in the BIM? *(*multiple choice question)*



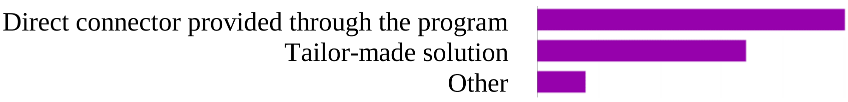
*others: different kind of technical specifications

Do you use any type of database outside the BIM model? *(*multiple choice question)*



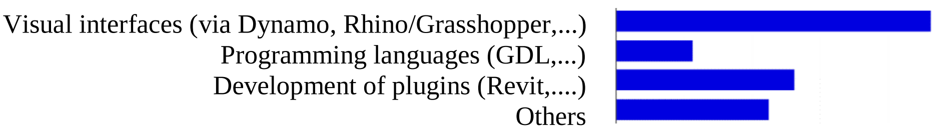
*others: RushForTools and those provided by the FM provider

Mechanisms for linking the BIM model with databases *(*multiple choice question)*



*others: through Dynamo and linking to Google Drive

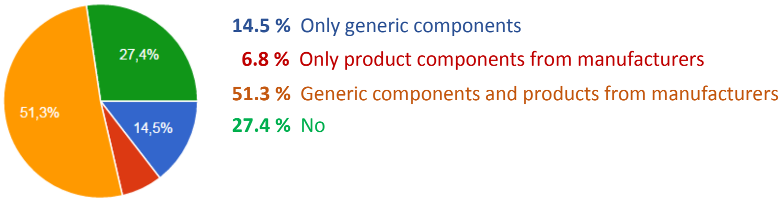
Experience at a technical/programming level with BIM technologies *(*multiple choice question)*



*others: Mainly none or in the learning process

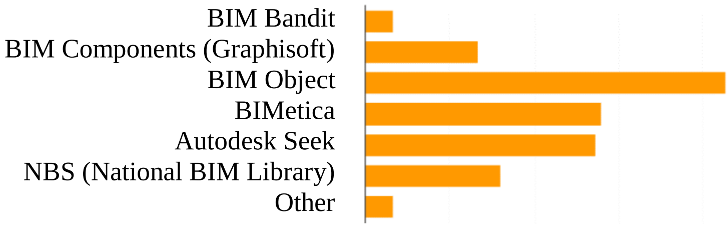
8.1.9. Components and products

Using external component libraries for BIM modelling



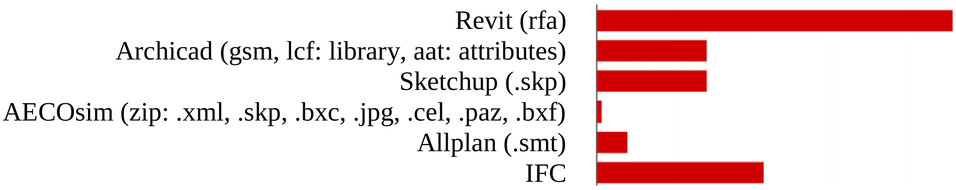
What external libraries do you visit to download BIM components/products?

*(*multiple choice question)*



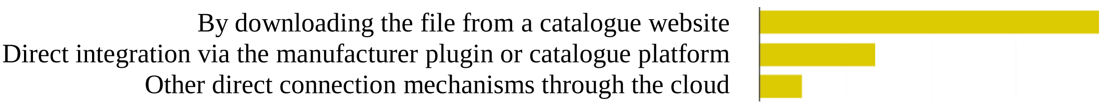
What kind of formats of BIM components/products do you download?

*(*multiple choice question)*

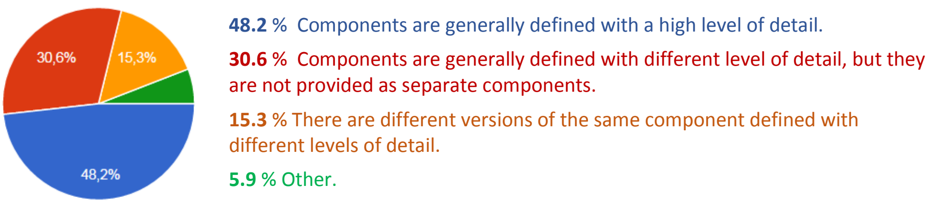


How do you integrate BIM components from external libraries into the BIM model?

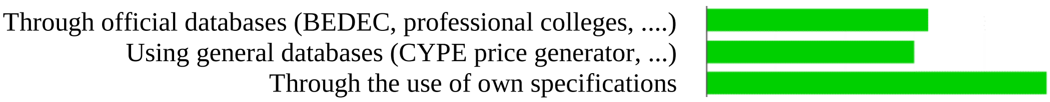
*(*multiple choice question)*



Level of detail of the BIM objects provided in building component catalogues

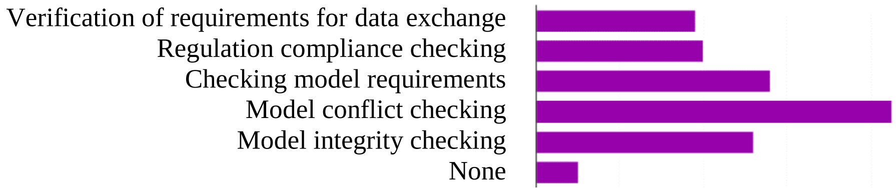


How do you define generic components? *(*multiple choice question)*

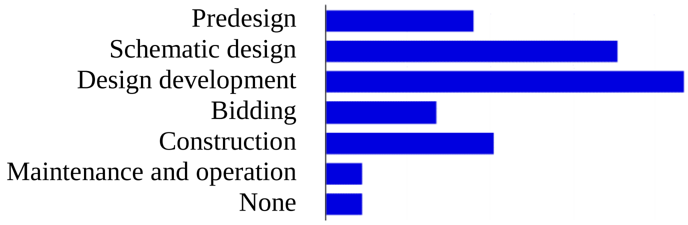


8.1.10. Checking

Use and type of checking *(*multiple choice question)*

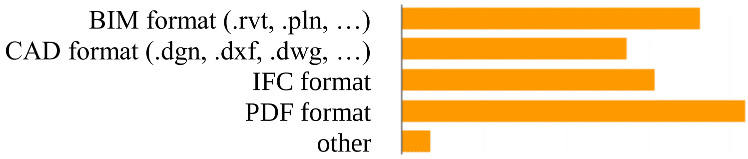


Phases in which practitioners carry out checks on the model *(*multiple choice question)*



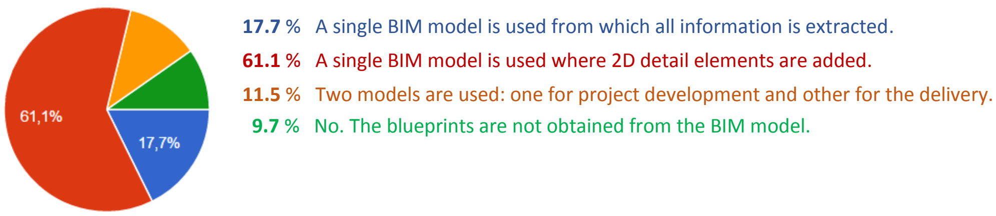
8.1.11. BIM delivery documents

BIM project deliveries *(*multiple choice question)*



*others: BIMx, blueprints, BIM BOX, Tekla BIMSight

Use of BIM in projects



This survey was developed with the collaboration of the following participants: Gonçal Costa, Miquel Rodríguez, Diego Vidoni, David Delgado, Agustí Jardí, Carolina Jarreta, Luis Manuel Sagredo, Álvaro Martín and Maria Elena Pla among other members of the BIM user community of Catalonia.

Aquesta Tesi Doctoral ha estat defensada el dia ____ d________________ de 201__

al Centre____

de la Universitat Ramon Llull, davant el Tribunal format pels Doctors i Doctores sotasignants, havent obtingut la qualificació:

President/a

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Vocal

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Vocal *

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Vocal *

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Secretari/ària

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Doctorand/a

(*): Només en el cas de tenir un tribunal de 5 membres