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Abstract

In previous decades, controlling the environmental impact through lifecycle analysis has become a topical issue in the building sector. However, there are some problems when trying to exchange information between experts for conducting various studies like the environmental assessment of the building. There is also heterogeneity between construction product databases because they do not have the same characteristics and do not use the same basis to measure the environmental impact of each construction product. Moreover, there are still difficulties to exploit the full potential of linking BIM, Semantic Web and databases of construction products because the idea of combining them is relatively recent. The goal of this thesis is to increase the flexibility needed to assess the building's environmental impact in a timely manner. First, our research determines gaps in interoperability in the AEC (Architecture Engineering and Construction) domain. Then, we fill some of the shortcomings encountered in the formalization of building information and the generation of building data in Semantic Web formats. We further promote efficient use of BIM throughout the building life cycle by integrating and referencing environmental data on construction products into a BIM tool. Moreover, semantics has been improved by the enhancement of a well-known building-based ontology (namely ifcOWL for Industry Foundation Classes Web Ontology Language). Finally, we experience a case study of a small building for our methodology.

Key words: Semantic Web, Building Information Modelling, Ontologies, Environmental Product Declaration databases, Sustainability of buildings.

Résumé

Au cours des dernières décennies, la maîtrise de l'impact sur l'environnement par l'analyse du cycle de vie est devenue un sujet d'actualité dans le secteur du bâtiment. Cependant, il y a quelques problèmes déchange d'informations entre experts pour la réalisation de diverses études telles que lévaluation environnementale du bâtiment. Il existe une hétérogénéité entre les bases de données de produits de construction car elles n'ont pas les mêmes caractéristiques et n'utilisent pas la même base pour mesurer l'impact environnemental de chaque produit de construction. En outre, il est encore difficile d'exploiter pleinement le potentiel de liaison entre le BIM, le Web sémantique et les bases de données de produits de construction, car l'idée de les combiner est relativement récente. L'objectif de cette thèse est d'accroître la flexibilité nécessaire pour évaluer l'impact environnemental du bâtiment au moment opportun. Premièrement, notre recherche détermine les lacunes en matière dinteropérabilité dans le domaine AEC (Architecture Engineering and Construction). Ensuite, nous comblons certaines des lacunes rencontrées par la formalisation des informations du bâtiment et la génération de données du bâtiment aux formats Web sémantique. Nous promouvons l'utilisation efficace du BIM tout au long du cycle de vie du bâtiment en intégrant et en référençant les données environnementales sur les produits de construction dans un outil BIM. De plus, la sémantique a été affiner par l'amélioration d'une ontologie bien connue basée sur le bâtiment ; à savoir ifcOWL pour le langage d'ontologie Web (OWL) des IFC (Industry Foundation Classes). Enfin, nous avons réalisé une expérimentation d'une étude de cas d'un petit bâtiment pour notre méthodologie.

Key words: Web Sémantique, Building Information Modelling, Ontologies, Bases de données Environmental Product Declaration, Durabilité des bâtiments.

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LIST OF SYMBOLS AND ABBREVIATIONS

BIM . .	Building Information Modelling
IFC . .	Industry Foundation Classes
EPD . .	Environmental Product Declaration
gbXML	Green Building XML
OWL .	Web Ontology Language
RDF . .	Resource Description Framework
RDFS .	Resource Description Framework Schema
SPARQL	Simple Protocol and RDF Query Language
SWRL .	Semantic Web Rule Language
RuleML	Rule Markup Language
URI . .	Uniform Resource Identifier
API . .	Application Programming Interface
DXF . .	Drawing eXchange Format
DWG .	DraWinG
NBDM	Neutral Building Data Model
XML .	Extensible Markup Language
NRM .	New Rule Management
BLC . .	Building Life Cycle
LCI . .	Life Cycle Inventory
LCIA .	Life Cycle Impact Assessment

GENERAL INTRODUCTION

0.1 CONTEXT OF MINDOC

Global warming is the phenomenon of increasing the average temperature on the surface of the earth over several years. Being an actual issue worldwide, global warming is caused by the increase of greenhouse gases in the atmosphere, which in turn increases the greenhouse effect. The greenhouse effect is a natural phenomenon that consists of an increase in temperature on the surface of the earth for the survival of the planet earth (Météo-France, 2019). Human activity produces disproportionate amounts of so-called greenhouse gases, in addition to those naturally occurring in the atmosphere, which results in an additional greenhouse effect, largely responsible for the current global warming. Among these activities, the most contributors to the emission of greenhouse gases are: the use of fossil fuels, the exploitation of tropical forests and the breeding of livestock (Commission, 2019). These activities emit several greenhouse gases including 77% of CO_2. CO_2, mainly emitted by the combustion of energy, is the main greenhouse gas generated by human activity (Crutzen et al., 1979). This last observation makes the reduction of energy consumption a very current and realistic goal for a slowdown in global warming, for the preservation of our planet. Hence the need to revisit the processes of the most energy-consuming activities, noticing that industry sectors do not contribute equally to the warming (Herzog, 2009).

Indeed, studies have shown that the building sector in France consumes nearly 45,5% of the energy produced each year. This implies 22% of greenhouse gases emitted (MTES, 2018). Building sector is also the first consumer of non-renewable raw materials and the largest producer of waste. These impacts are generated during the building's operational phase but also during its construction and end of life. In addition, environmental impact assessment of buildings is not mandatory in most country like France. In this way, improving the methods used in the building sector, particularly those related to the choice of construction products, would significantly contribute to reduce the environmental impact of the building and thus preserve our environment. The ideal would also be to lower the cost of buildings while improving the comfort of users. Put together, environment, economic and social criteria enable the gauge of the sustainability of a building. This thesis focuses on environmental aspect of the sustainability. To assess the environmental impact, more and more environmental assessment tools are used. But these still require a significant improvement and more interactions with most recent tools and technologies in AEC industry.

0.2 ISSUES

The building is a complex object consisting of a set of products that each has a life cycle in which they impact more or less the environment. This means that each product in the building has its own life cycle that begins before it belongs to the building and ends at the end of its life in or outside the building. These products range from concrete used to pour the slab or wood used for the floor, to the door or window that is installed in a particular part of the building. Moreover, a construction project is a complex project involving a very large number of stakeholders who encounter interaction problems, especially in terms of information exchange: the latter are also called interoperability issues. Interoperability is the ability of diverse systems, organizations and/or individuals to work together, using the parts or equipment of each other, to achieve a common goal, regardless of their divergences (Ide & Pustejovsky, 2010). Given the difficulties of interaction faced by the various actors involved in the construction project of a building, there is still a long way to go before significantly lowering above-mentioned alarming numbers.

Since many years now, Building Information Modelling (BIM) has been introduced to collect and share a set of data about a building throughout its lifecycle. BIM facilitates collaboration between various construction industry software that revolve around the digital model of the building. These software include, among others, architectural design, economic, thermal, HVAC, fluid and structure engineering and environmental software. Moreover, address information exchange issues in building sector were part of the goal of BIM. In addition, experts have suggested with some success the combination of Artificial Intelligence technologies to BIM, in order to overcome interoperability issues encountered (Abanda et al., 2013). Initiated in 2016 and funded by Occitanie Region in France the MINDOC project is in line with this framework by aiming to combine BIM, Semantic Web technologies and construction products databases to decrease the environmental impact of the building; by addressing information exchange issues.

0.3 OUR CONTRIBUTIONS

The contributions of this dissertation are divided into three main parts: An approach for the integration of multiple EPD databases and the inclusion of environmental data in building data; an approach for the development of a plugin for a BIM tool to make environmental data on construction products available in a common BIM tool; and a methodology for the enhancement of a well-known BIM-based ontology. These parts are very well connected and related to each other, but they are presented separately in order to aid understanding of the benefits, functionalities and capabilities added to improve the sustainability of building industry by each part.

Approach of integration of multiple EPD databases This contribution develops our framework for gathering data from various environmental data, generating ontologies regarding the semantics and structure of the data. In addition, it explains the process of integrating multiple environmental databases. Finally, the alignment of construction product ontology with building-based ontologies is introduced.

Approach of making environmental data on construction product available in a common BIM tool This contribution introduces and implements our framework to make environmental data on construction products available at early stages of the building lifecycle, and without the need of learn a new software tool. The implementation part is the development of a plugin which loads integrated environmental data from a triplestore to the user interface of Autodesk Revit software.

Enhancing the Semantic Interoperability of BIM Systems This contribution introduces a strategy for enhancing information exchange in BIM by advancing semantic interoperability of software tools. It provides a critical analysis of the ifcOWL ontology. In addition, it points to semantic interoperability issues with ifcOWL and shows how these issues can be resolved by using a top-level architecture. Finally, the restructured ontology is evaluated in comparison with the existing ifcOWL ontology.

0.4 THESIS STRUCTURE OUTLINE

In Chapter 1 the background of the MINDOC project is introduced. It provides the reader with the basic knowledge of the concepts, tools and technologies used. The aim of this chapter is to describe each element with regard to the goals and the methodology of MINDOC project, in order to support the reader understanding of the other parts of this document.

In Chapter 2, State Of The Art in relation with the context of MINDOC project is introduced.

In Chapter 3, we present our method to make environmental data available at early phases of the building lifecycle, and its implementation for a use case. Semantic web technologies and particularly Linked data have been combined to Building Information Modelling (BIM) and databases of construction products to foster building sustainability.

Chapter 4 describes a strategy for enhancing information exchange in BIM by advancing semantic interoperability of software tools. In our work, upper level ontologies combined with the addition of descriptions and definitions to a well known BIM-based ontology are experienced.

Chapter 5 provides the link between our previous contributions by describing our use case and its instantiation with all MINDOC ontologies and compare the results with the State Of the Art. It further describes main directions on building blocks towards a MINDOC Sustainable Decision Support (MINDOC SDS) tool and discusses on future works.

The Figure 1 presents the overall structure of the research conducted in this thesis.

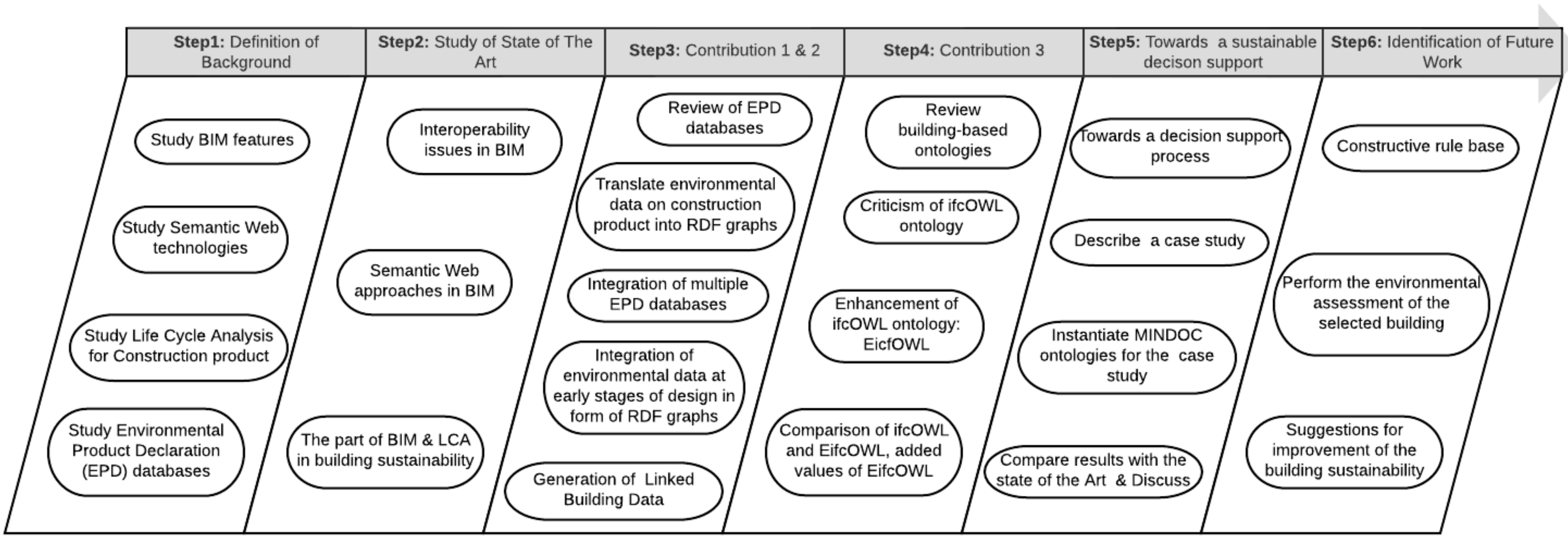

Figure 1: Overall structure of the research process

CHAPTER 1

Background of the thesis

INTRODUCTION

This chapter defines the background of the thesis by introducing various terms and technologies that will be addressed throughout this document. First, the motivations to use certain tools and technologies are explained. Then, we will present Building Information Modelling (BIM). Moving on, we will explain Semantic Web Technologies. Finally, Life Cycle Assessment and environmental data will be explained.

1.1 DEFINITION OF THE BACKGROUND

In view of the context of the MINDOC project, and to achieve defined goals while solving above mentioned problems, many concepts, technologies and tools exist. We need a structure capable of holding building data along the building lifecycle. In addition, data that are represented need to be formalized in order to address information exchange issues faced by experts. For these elements combined to contribute to the sustainability of the building to be built, it is essential that the experts have at the right time, relevant information to assess the environmental impact of the building. The build-up of solution involves:

- **The Building Information Modelling(BIM).** BIM is a tool that collects and shares a set of data about a building throughout its lifecycle. BIM is capable of holding building data along the building lifecycle. This makes it possible to obtain a 3-dimensional model of the building but also detailed information on each object composing the building: the geometric characteristics, the type of material used, the manufacturer, etc (Strafaci, 2008). This makes BIM a valuable tool that can be used for a variety of building-related studies. To carry out an environmental assessment of a building, requirements are materials, quantities of materials, equipment, material renewal frequency, energy consumption, water consumption, etc. All these data are available in the BIM, since they are necessary for structural and thermal design, building maintenance, etc. All the data for conducting the environmental assessment are, therefore "naturally" available in the BIM. Ideally, there should be no further information to seek if all the information was actually shared by all experts.

- **Semantic Web Technologies.** They are a set of standards aimed at facilitating the exchange of data on the web through the use of standardized data formats and exchange protocols. Ontologies, which are the formalization of knowledge of a domain, as well as graphs of data, are part of Semantic Web technologies. In the literature, Semantic Web Technologies have demonstrated their ability to contribute to solving the interoperability problems faced by BIM experts throughout the building life cycle (Pauwels et al., 2010). Ontologies are especially used in combination with some BIM data formats.

- **Life Cycle Analysis of the building:** results from the life cycle analysis of each of its components (Asdrubali et al., 2013). It shows that the choice of building materials and products is decisive as to the overall environmental impact of the building, although the consumption of energy, water, waste generation etc. during the use phase of the building must also be taken into account.

1.2 BUILDING INFORMATION MODELLING(BIM)

To monitor a building throughout its life cycle, there are various tools. One of them is BIM. As defined in literature, BIM is both a process, a product, a technology set, a tool or a software category. For NBIMS-US (National BIM standards - United States), BIM is a digital representation of physical and functional characteristics of a facility (East & Smith, 2016). BIM is a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its lifecycle. It can be used from earliest conception to demolition or refurbishment. More condensed, BIM can be defined as a concept which holds various purposes at different levels. The model part of BIM is the 3D digital representation of the building and all related data. BIM tool/software category consolidates information about the building from the sketching phase to its demolition or renovation. BIM maintains a shared knowledge of a 3D model of a building. It provides to building professionals the insight to more efficiently plan, design, construct, and manage buildings.

1.2.1 BIM features

Unlike the Computer Aided Design (CAD) in 3D, BIM described the construction project into its components (Kensek & Delcambre, 2015). The BIM includes both 3D graphics, a parametric model and information entered by actors (Architects, Engineers and Construction companies). BIM software mainly uses the volume technique to represent a building: a building would be an assembly of blocks of elements. To each of these blocks, the BIM associates parameters that can enrich it to different degrees. Depending on how the information is derived from the BIM, different "dimensions" of the BIM are defined: 2D BIM, 3D, 4D, 5D, and even 6D or 7D (Sacks et al., 2016).

- 2D BIM refers to the two-dimensional drawing.
- 3D BIM refers to the digital 3D model. In practice, several models are designed with different levels of development according to the intended uses. 3D models are made for all phases of study and construction. Unlike 2D BIM, the resulting database of 3D BIM can be exploited to calculate rendering images, check for interference, for the regulatory audit, for simulations or for performance predictions.
- 4D BIM represents the integration of time with the 3D model.
- BIM 5D adds the economic aspect (Smith, 2014).
- BIM 6D introduces the concepts of life cycle, maintenance and energy management elements (Nicał & Wodyński, 2016).
- BIM 7D addresses security issues within the building while BIM 8D seems to address accident prevention and safety in building as proposed by Kamardeen (2010).
- BIM 9D addresses environmental aspect of the building and all its components, as an entire part of the infrastructure sustainability. The concept of 9D BIM is first introduced in the context of this thesis.

1.2.2 BIM standards

To accomplish BIM features, several standards have been introduced in BIM (Azhar et al., 2012; Jung & Joo, 2011). First, the Industry Foundation Classes (IFC) has been introduced by Industry Alliance for Interoperability (IAI) to provide an interoperable environment for IFC-compliant software applications in the AEC/FM industry (Bazjanac & Crawley, 1997; Wix & Liebich, 1998). In addition, IFC allows the acquisition of building geometry and other building data from project models created with IFC-compliant software. Moreover, there is STEP which stands for Standard for the Exchange of Product model data. It is an ISO[1] standard for the computer-interpretable representation and exchange of product manufacturing information. However, the first "BIM standard" has been implemented in 2018: the ISO 19650. It is an international standard to manage information using building information modelling (ISO 19650-1).

1.2.3 BIM benefits

BIM benefits list is extensive as is its list of beneficiaries. The recipients of the BIM range from Owners, planners, realtors, appraisers, mortgage bankers, designers, engineers, estimators, specifiers, facility managers, safety engineers, occupational health providers, environmentalists, contractors, lawyers, contract officers, subcontractors, fabricators, code officials, operators, risk managers, renovators, first responders and demolition contractors (Kensek & Delcambre, 2015).

The immediate benefit of BIM for Architecture Engineering and Construction/-Facility Management (AEC/FM) industry is a better designs, productivity and an increase of efficiency. BIM also significantly reduce the time to evaluate more alternatives, execute design changes, and produce construction documentation, because design and construction documentation are dynamically linked. In addition, BIM facilitates building construction industry process optimization by including

[1] ISO 10303: Automation systems and integration Product data representation and exchange

visualization, simulation, and analysis as part of the design process. Information raised by BIM goes from geometric characteristic of each object of the building, to cost, energy or structural related data (Kensek & Delcambre, 2015). BIM can also enable early error detection and the collaboration of multiple disciplines. That makes it a valuable tool for diverse studies around building project construction. However, potentialities are not yet fully exploited because of issues.

Following are two examples of scenario that usually occur during a building lifecycle. In the design phase, a ramp for people with reduced mobility must imperatively be installed at a second entrance of the building. By adding the necessary elements to the 3D digital model, the changes are immediately reflected on the entire building. Thanks to BIM, long hours of rescaling have been spared. A storm hit the city yesterday and smashed the building's emergency door. Thanks to the BIM, the building manager has access to all information relating to the door: dimensions, types of materials constituting it, model, manufacturer, date of installation of the door, etc. In a few clicks, the manager carries out the order of a door identical to that deteriorated. With BIM, the maintenance phase of the building is simplified, cheaper and more likely to preserve the facility.

1.2.4 BIM tools

There exist several kinds of BIM tools: from generalist tools to ones addressing only specific cases (Nagy et al., 2015).

1.2.4.1 Generalist BIM tools

Among the general-purpose BIM tools, Autodesk and Bentley Systems distinguish themselves the quantity and variety of tools they offer.

Autodesk Autodesk's offering primarily includes the suites Autodesk Building Design Suite, a number of applications and Autodesk 360 offer. The Autodesk Suite tools combined make it possible to optimize constructibility, design at objective costs, and optimize the building process.

Autodesk Building Design Suite is a range of software for 3D building designing. It gatherers BIM and CAD tools. Those tools further enable access to simulation and integrated analysis tools with created visualizations.

Used by project owners, the **Autodesk Revit** application has various functions and a multiplicity of trades to which it is addressed. It includes functions for architectural design, fluid engineering and structure and construction engineering.

As a synthesis tool for the BIM manager, **Autodesk Navisworks** enables a variety of professionals to comprehensively review integrated data and models with stakeholders for increased control over project results. Before the start of construction or renovation, it provides teams with integration, analysis and communication tools to help them coordinate disciplines, resolve conflicts and plan projects.

Autodesk 360 is an online service platform for centralizing the digital model on a server accessible by all and with all types of access. These services range from exchanging documents (BIM, CAD, text, etc.), to simulating the building's energy performance (Autodesk Green Building Studio and Autodesk Conceptual Energy Analysis), as well as image rendering (Autodesk 360 Rendering), online collaboration in the Cloud (Autodesk BIM 360 Glue), data transport on a mobile platform on the site and the ground, and many others.

Bentley Systems provides software solutions dedicated to infrastructures, for architects, GIS specialist, owner-operator and engineers. It proposes 3 solutions: MicroStation, ProjectWise and AssetWise. Each solution is made of a set of interoperable applications that can be supplemented by professional services available worldwide. Bentley Systems is specialised in technical software of information modelling for projects integrated to smart infrastructures in various area. These domains include but are not limited to buildings, bridges, roads, transit and rail networks, construction simulation, collaboration services, 3D city modelling, etc.

Nemetschek Evolving from CAD to BIM Nemetschek has specialized in wealth management. It aims to cover all phases of the life cycle of a project while ensuring full interoperability. For this reason, Nemetschek provides a set of BIM-compatible and interoperable construction industry software that cover the entire lifecycle of buildings.

1.2.4.2 Non-Generalist BIM tools

The non-generalist BIM tools are those of construction industry software that are able to exchange and manipulate BIM data and interact with generalist BIM tools. Among others, there are HVAC system and plumbing design tools, thermal analysis tools, environmental assessment tools, and economic tools. The Figure 1.1 presents a BIM Diagram.

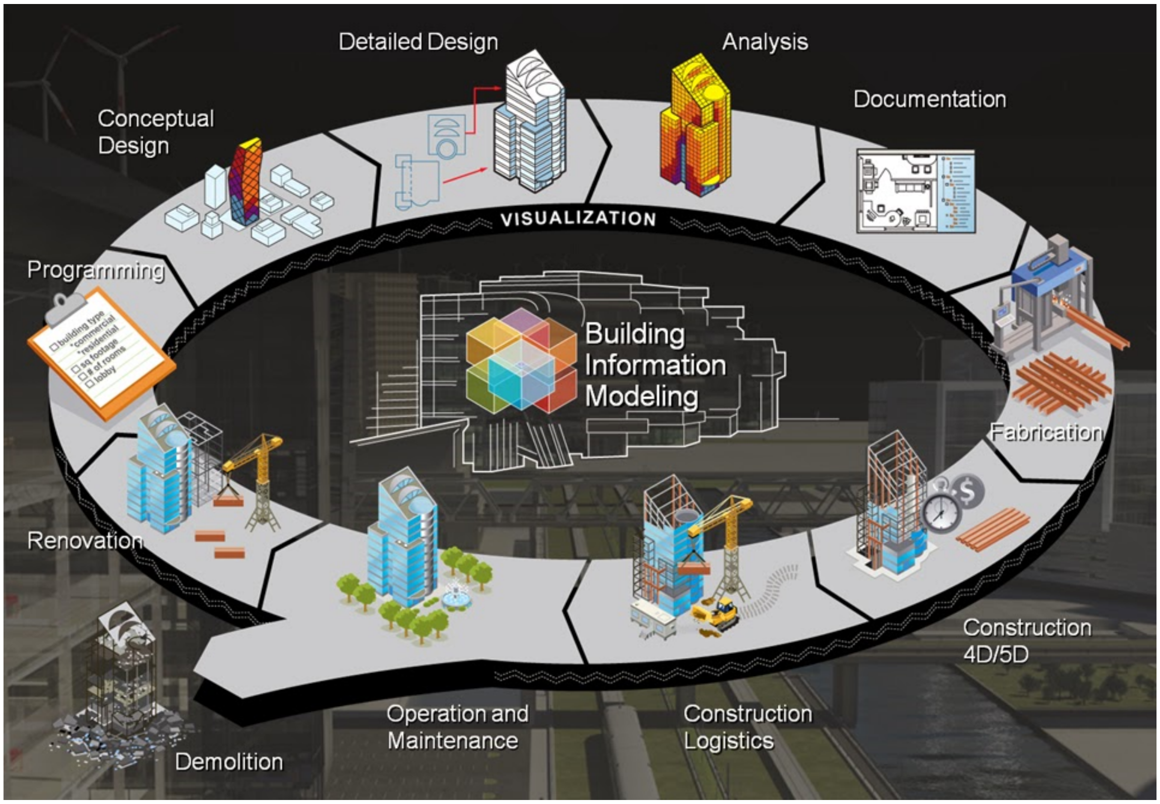

Figure 1.1: BIM Diagram (Image from buildipedia.com)

In the ensuing paragraphs, only thermal, environmental and costing evaluation/design tools have been described and not structural dimensioning tools for example. That is because first tools could provided the necessary data for an environmental assessment tool.

Thermal or energy analysis tools

- **Clima-Win** is a built-in thermal calculation software for calculating piece-by-piece losses according to EN 12831, the RT2012[2] calculation using the CSTB calculation engine (rt batiment.fr, 2019; LSE, 2019), the existing standard TR (Thermal Regulation) and the existing TR elementary calculations, to name a

[2] *Réglementation Thermique 2012* or French Thermal Regulation 2012

few. From a single input, Clima-Win performs all calculations using a digital model built into the software. It can also import graphic input in image format, DXF, DWG, NBDM, gbXML and IFC. However, two conditions must be satisfied for an IFC model to be usable in Clima-Win: The spaces present in the building, as well as the adjacencies between parts must be identified.

- **ArchiWizard** is supplied with 3D digital mockup software. It performs calculations and thermal simulations in real time from a digital model imported from CAD software. This software is used throughout the preliminary draft phase to inform the user about the performance of his project and thus help him to position himself in major architectural and technical choices.

- **Pleiades** is a software for eco-design of buildings and neighborhoods. Diverse types of calculations can be performed from a graphical input or digital model: thermal and energy simulation, regulatory verification, equipment sizing or statistical analysis.

Economic tools: Attic+ solutions

- **WinQUANT Q4** is a software based on a 3D engine for the management of written documents (quantitative, estimates and the special technical specifications book). It allows estimates / metrics and graphical inputs from Digitizer, PDF, JPEG, BMP, DXF and IFC.

- **Easy-KUTCH** is a 2D-3D calculator allowing companies to come up with the special technical specifications book, the estimated quantitative detail and many others, by associating graphic quantities with a catalog of articles and generalities.

- **IFC Interface** allows WinQUANT Q4 and Easy-KUTCH to establish estimates, metrics and specifications of particular technical clauses from projects made with any CAD software that can work in 3D and IFC compatible. In addition, this interface allows the recovery of project geometry in WinQUANT. Compatible with IFC version 2x3 and later, the IFC Interface allows interaction with ArchiCAD, AutoCAD Architecture, Revit, Allplan, etc.

Environmental assessment tools

- **Elodie & eveBIM:** is a lifecycle analysis tool developed by the CSTB[3]. It is dedicated to the building and allows to synthesize the different environmental impacts of materials and construction products, on the entire structure and on its life cycle. Elodie software also measures the environmental impact of buildings on their life cycle. It takes into account the environmental impacts not only of the energy consumption of the building, but also the contributions of building products, the water consumption of buildings, and many others. Coupled with eveBIM, Elodie makes it possible to compare the different contributors to the consumptions of energies of a work according to different criteria.

- **FDES[4] in IFC:** INIES is a life cycle analysis database dedicated to construction products. This is the French reference base for FDES. For each construction product, it lists life cycle inventories, raw materials, energy, water consumption and emissions in water, air or soil. The results are presented in the form of environmental indicators. In 2010, CSTB and BuildingSmart teamed up to introduce FDES environmental indicators in the IFC2x4 version via the

[3]CSTB = *Centre Scientifique et Technique du Bâtiment* http://www.cstb.fr/fr/

[4]*"Fiche de Déclaration environnementale et Sanitaire"*

set of properties:
PSET_environmentalImpactIndicators. This allows the coupling of Elodie and EveBIM software with the INIES database for exploitation of the building digital mock-up in IFC format. This coupling ensures the interoperability necessary to perform a lifecycle analysis on a building for which the digital model is available in IFC format. However, the later fully depends on the IFC file format used, here IFC2*4, which is obsolete nowadays.

- **Cocon-BIM:** is a software dedicated to the study of the environmental quality of materials and buildings and life cycle analysis through BIM. Capable of performing LCAs compatible with the "energy-carbon" label E + C-, it complies with the European standards EN 15643 and EN 15978.

1.3 SEMANTIC WEB TECHNOLOGIES

Berners-Lee et al. (2001) claim that the goal of Semantic Web technologies is to enable machines to grasp semantic documents and data. To achieve specified goal, many technologies coexist in a single architecture called the Semantic Web technology stack.

Figure 1.2 shows the Semantic Web stack.

1.3.1 Identifiers ans locators

Uniform Resource Identifier (URI) is a fundamental point in web stack. It is an unique identifier format for naming and referencing any resource on the web. They can give the path to get a representation of this resource (URL) or be internationalized (IRI). The HTTP protocol is also an essential element of the stack as it makes it possible, from a URL address, to request a representation of the resource identified and localized by this URL and to obtain in return either the data of this representation or an error code indicating a problem encountered. Another fundamental notion is HTML, a language to represent, store and communicate web pages (Gandon et al., 2012).

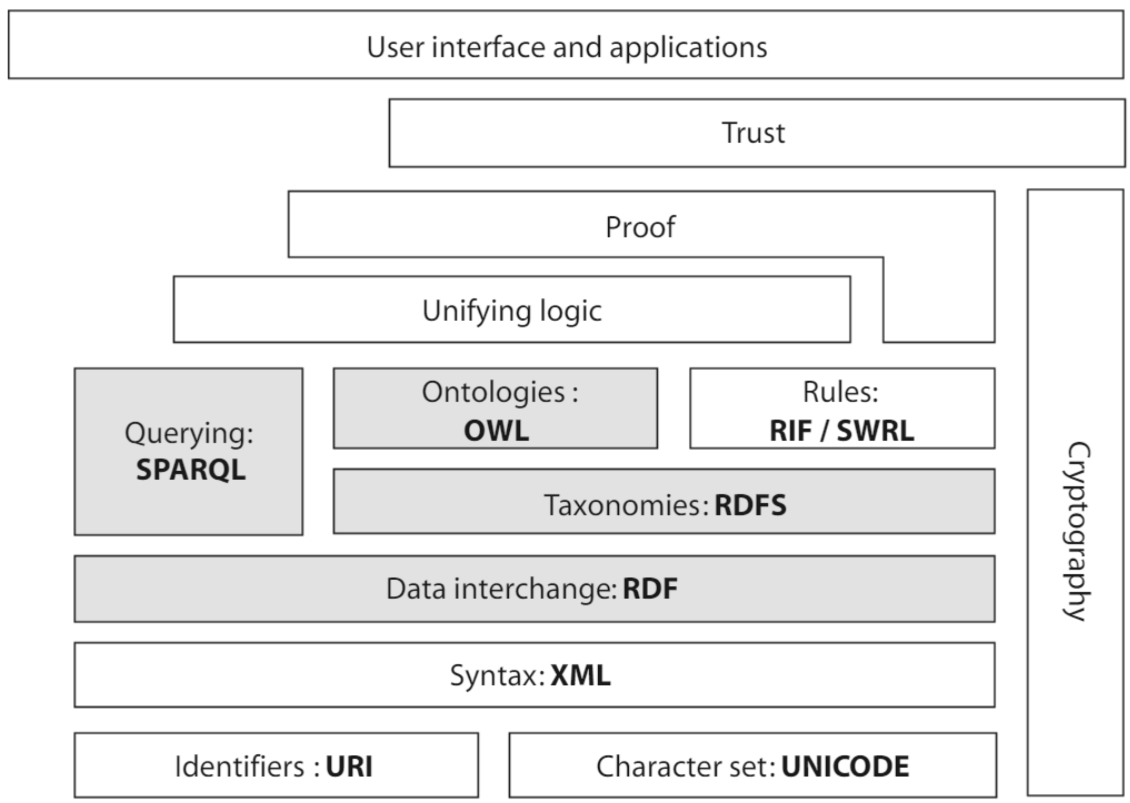

Figure 1.2: Semantic Web technology stack (Gandon et al., 2012).

1.3.2 RDF & RDFS

Resources Description Framework (RDF) is the first brick of Semantic Web standards and covers several standards and models: XML, Turtle, etc. Being part of the W3C RDF Primer (Manola et al., 2010; Schreiber & Raimond, 2014), RDF is a directed, labeled graph data format for representing information in the Web. RDF covers both a template and several syntaxes including XML, Turtle and RDFa, to publish data on the web.

RDF Schema (RDFS) aims to define the vocabularies used in RDF graphs and name its primitives with URIs. These primitives are the class resources and the types of relationships that exist between these classes. By providing URI for types, RDFS provides hierarchies of resource types, allowing inferences to be made, for example, to infer that a Window resource is also of type Hole. The taxonomic skeleton thus obtained with universal, exchangeable and reusable identifiers would notably allow the interoperability of the systems (McBride, 2004). They are many things that cannot be expressed in RDFS like transitivity, inverse relations and OWL comes to overcome some of these lacks.

1.3.3 Web Ontology Language (OWL)

W3C defined OWL as "a Semantic Web language designed to represent rich and complex knowledge about things, groups of things, and relations between things" (OWG, 2012; McGuinness et al., 2004). Designed for use by application that need to process the content of information, OWL greatly facilitate interpretability by providing additional vocabulary along with a formal semantics. It is used for ontology design.

This work follows Arp et al. (2015) in viewing an ontology as a kind of representational artifact whose purpose is to capture what is general in reality by representing universals, defined classes and the relations between them using some combination of definitions, axioms, rules and constraints. The backbone of an ontology is its hierarchy of terms, which are joined together by what are called is_a for "is a subclass of" relations. This backbone is supplemented by other relations such as part_of holding between the entities represented by these terms (Smith, 2003). The goal of ontology is to enable knowledge sharing and reuse by means of a definitive classification of entities in specific domains constructed on the basis of a controlled vocabulary with logical definitions of its terms. To achieve this goal, the content of an ontology should be validated by human experts in the corresponding domain, specifically - for our purposes here - the domain of buildings and construction (Arp et al., 2015; Gruber, 2009).

There are many kinds of ontologies depending on the level of specification for a specific domain or application, as specified by Horridge et al. (2004), Arp et al. (2015) and Chandrasekaran et al. (1999) .

- **Top-level ontology** consists in very general terms that are common across all domains (Arp et al., 2015).
- **Middle-level ontology** can be used for a bunch of domains.
- **Domain ontology** enables the assertion of specific proposition about a domain or a situation in a domain (Guarino, 1997).
- **Application ontology** contains definitions that are specific to a particular application (N. et al., 2009).

1.3.4 Simple Protocol and RDF Query Language - SPARQL

Used to express queries across diverse data sources, SPARQL is a query language in the Semantic Web. The data can be whether stored natively as RDF or viewed as RDF via middleware (W3C, 2008). SPARQL for the Web of Data is comparable to SQL for relational databases.

1.3.5 Semantic Web Rule Language - SWRL

Intended to be the rule language of the Semantic Web, SWRL is based on a combination of OWL and RuleML and has a formal semantics (Submission, 2004). Moreover, SWRL includes a high-level of horn-like rules and enable the expression of rules in terms of OWL concepts: classes, properties and individuals; thus, it is of great usage to access and evaluate OWL.

1.3.6 Linked Data

Linked Data, also called the Web of Data is data available as RDF graphs, that provides an extension of the Web by enabling sharing and publishing of raw data with the use of open standards (Heath & Bizer, 2011): RDF, URI, SPARQL, etc. Available data are linked into a semantic network of data, in which each property and resource has a web-based URI as well as an internationally unique identifier. These graphs can subsequently be stored in a triplestore. A triplestore is a purpose-built database that stores semantic facts in the form of RDF graphs, against which queries can be made in SPARQL (ontotext.com, 2018).

1.4 ENVIRONMENTAL ASSESSMENT OF BUILDINGS

1.4.1 Life Cycle Assessment (LCA): The main tool for environmental assessment

LCA is a methodological framework to assess environmental impacts associated with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling (defined in the DIN ISO 14040/44). Rashid & Yusoff (2015) define LCA as a methodology framework to estimate and evaluate the environmental impact throughout a product life cycle from cradle to grave. They divide it into four steps:

- Step 1: Definition of goals and scopes
- Step 2: Life Cycle Inventory (LCI)
- Step 3: Life Cycle Impact Assessment (LCIA)
- Step 4: Interpretation

These steps can become very difficult to execute on some products like buildings because they are complex. Many life cycle assessment methods exist and some of them have been used to constitute LCA databases. Rashid & Yusoff (2015) and Suh & Nakamura (2007) distinguishe 3 LCA methods: process-based LCA, Economic Input-Output LCA (EIO-LCA) and hybrid LCA (combination of the two others), process-based being the most used in LCA research, even if it is more complex and time consuming than EIO-LCA. The four steps above-mentioned describe the process-based LCA. EIO-LCA models represent monetary transactions between industry sectors in mathematical form. They indicate what services are consumed by other industries (Institute, 2016).

Each methodology of LCA research in the building industry respond to a predetermine system boundary, functional unit and building lifespan. Gate-to-gate, cradle-to-gate or cradle-to-grave are commonly used building's LCA system boundary; cradle-to-grave being the most used. Functional unit and system boundary are determined in the first step of LCA: the Goals and scopes study. Functional unit defines the quantification identified functions of the selected product to ensure comparability.

The environmental impact of a building refers to all qualitative, quantitative and functional changes in the environment (negative or positive) generated by the building from its design to its "end of life". The environmental impact study is required to conduct a life cycle analysis of the building (ISO 14001:2015). Environmental impact indicators are related to the state of the environment and its uses. They provide a means of quantifying the damage caused to the environment.

Goals of LCA in AEC/FM domain are to calculate the embodied impacts in all design stages while being consistent with the results from the completed building project, and estimate the final embodied environmental impact with increasing accuracy and provide information for decision making throughout the whole design process (Cavalliere et al., 2019). LCA encounters some issues that hinders its full potential:

- The buildings lifespan is spread out over time and they are made up of multiple other products that deserve each particular attention since each has a life cycle of its own.
- The difficulty in assessing environmental properties for building components.
- The difficulty in assessing sustainability-related data.

It is thus important to master every single LCA in order to realize a proper LCA for the whole building. Moreover, BIM data schema present inadequacy to semantically represent sustainability-based knowledge.

There are some Government actions for sustainability of construction in France to reduce the environmental impact of buildings:

- The PACTE[5] program to foster construction quality and energetic transition

[5] *"PROGRAMME DACTION POUR LA QUALITÉ DE LA CONSTRUCTION ET LA TRANSITION ÉNERGÉTIQUE"*

(AQC, 2019);

- The best practices program named *PROGRAMME RÈGLES DE L'ART GRENELLE ENVIRONNEMENT* 2012 (PRAGE). It aims to help the building sector to achieve the objectives set by the *Grenelle de l'environnement*, both in new and existing buildings (FFB, 2012).

1.4.2 Evaluation of the environmental quality of construction products

The aim of environmental assessment, independently of the object on which it is applied, is to ensure sustainability. The aim when performing the environmental assessment of the building, is to analyze the environmental impact of each of its components or any other relevant element, in order to ensure the sustainability of the building during its lifecycle (Schmidt, 2012).

Different methods of environmental assessment exist (Schmidt, 2012). This paragraph concentrates on their use in building industry, especially for the whole building or for a specific product that is part of it. During the environmental assessment of a building, fundamental elements used are: the application of an environmental assessment method (BRE, C2C, NF EN 15804, ISO 14025 ...) to each product constitutes an entry for an environmental database of construction products (INIES, Quartz, ...). Then the latter database is used to applied an environmental assessment method to the building (BREEAM, HQE, LEED, ...) perhaps using an environmental assessment software (Elodie & EveBIM, Cocon-BIM, ...).

Environmental Product Declaration (EPD) Results of LCA carried out for a specific product, organized in conformance to the standards ISO 14025, EN 15804+A1 and XP P01-064/CN, constitute an Environmental Product Declaration (EPD); which thus communicates the environmental performance of the product over its lifetime (Bionova, 2018; AFNOR, 2015). An EPD is an independently verified and registered document that communicates transparent and comparable information about the life-cycle environmental impact of products (EPDInternationalAB, 2019). Used in the INIES database, FDES[6] are the French EPDs. The standard ISO 14025:2006 considers several environmental impact indicators that are mandatory: global warming, ozone layer destruction, eutrophication, photochemical ozone creation, air acidification, flow indicators, primary energy and Water consumption. optional environmental impact indicators include, among others, the depletion of non-renewable natural resources, air toxicity, water toxicity and the production of hazardous waste.

Cradle-to-Cradle(C2C). McDonough & Braungart (2010) define C2C as a biomimetic approach to the design of products and systems that models human industry on nature's processes viewing materials as nutrients circulating in healthy, safe metabolisms. Initially launched by William McDonough (USA) and Michael Braungart (Germany), the C2C concept has been formalized and is used in several countries. It is progressively becoming a new paradigm for a more sustainable World. This paradigm works with nature rather than against it, using cyclical metabolisms of resource use that replenish as they consume. The C2C concept relies on three pillars: "Waste Equals Food", "Use Current Solar income" and "Celebrate diversity" (McDonough & Braungart, 2010).

BRE ENVIRONMENTAL PROFILES METHODOLOGY is " a standardised method of identifying and assessing the environmental effects associated with building materials over their lifecycle ". The aim of this method is, on one side to increase

[6] "Fiche de Déclaration Environnementale et sanitaire"

the credibility of suppliers and, on the other hand to provide to designers reliable and comparable environmental information about competing building materials (BREGroup, 2019b).

THE BRE GREEN GUIDE TO SPECIFICATION (BREGGS). Being part of the BREEAM, BREGGS is a "green guide" that contains more than 1500 specifications of building materials and components used in various types of building (BREGroup, 2019a). Data in BREGGS are ranked from A+ for the best environmental performance to E for the most environmental impact.

1.4.3 Environmental assessment methods for buildings

BRE ENVIRONMENTAL ASSESSMENT METHOD (BREEAM) BREEAM is a "sustainability assessment method for masterplanning project, infrastructure and building." Using standards developed by BRE, BREEAM delivers independent third party certification of the assessment of an assets environmental, social and economic sustainability performance. The main output of this process is the rating. Once certified, the latter reflects the performance achieved by a project and its stakeholders, as measured against the standard and its benchmarks (BREEAM, 2019). Ratings range from "Acceptable (In-Use scheme only) to Pass, Good, Very Good, Excellent to Outstanding". BREEAM measures sustainable value in many categories. Each of them addresses factors like low impact design, carbon emissions reduction, design durability, resilience, adaption to climate change, ecological value and biodiversity protection. The final performance rating is determined by the sum of the weighted category scores once the assessment of the development is complete.

Leadership in Energy and Environmental Design (LEED) Launched by the US Green Building Council, LEED is an American assessment method that evaluates multiple factors of the of the facility's environmental impact. Factors range from water consumption, energy efficiency, choice of the materials used, interior environmental quality to the innovation. Evaluated facilities include but are not limited to offices, institutional buildings, retail and services establishments, hotels and residential buildings. LEED certification is achieved by meeting all the prerequisites and earning a minimum number of credits for each of the above-mentioned categories. At the end of the evaluation process, a maximum of 100 points can be acquired with 6 additional points for innovation and 4 for regional priorities. Evaluation labels, also called excellence level of LEED are Certified, Silver, Gold and Platinium (ThemaVerde, 2019).

***Haute Qualité Environnementale* (HQE)** HQE is a global approach launched by HQE Association. It assesses the building's ability to meet 14 targets, which allow to perceive the factors that influence the environment. Thus, targets are evaluation criteria for which the building must comply in order to obtain the HQE label. Targets are divided into 4 main groups: Eco-construction targets, Eco-management targets, Comfort targets and Health targets. To be compliant, the building must obtain at least: 7 targets at the so-called "basic" level, 4 at the so-called "performance" level and 3 "high-performance" level (Alliance-HQE-GBC-France, 2019).

The E+/C- Label is a reference for new buildings. Set up by the French State, the E+/C- label foreshadows the future RE2020 regulation that will make the environmental assessment of construction mandatory in France. It uses a method to evaluate the energy and environmental performance of new buildings. This label attributes to the evaluated building, levels of performance characterized by (ADEME, 2019):

1. An "Energy" level based on the $Balance_{BEPOS}$ indicator. The evaluation of the performance of a building relating to the energy balance is made by comparison with a maximum energy balance level, Balance $BEPOS_{max}$: $Balance_{BEPOS} <=$ Balance $BEPOS_{max}$. There are 4 energy performance ratings: the "Energy 1", "Energy 2" and "Energy 3" levels show progressiveness in improving energy efficiency and the use of renewable heat and electricity for the building. The "Energy 4" level corresponds to a building with zero energy balance (or negative) on all uses and which contributes to the production of renewable energy at the neighbourhood level.

2. A "Carbon" level based on *Eges* (Indicator of greenhouse gas emissions over the entire life cycle) and $Eges_{PCE}$ (Indicator of Greenhouse Gas Emissions of Construction Products and Equipment Used). The assessment of the performance of the greenhouse gas emissions building is made by comparison with a maximum greenhouse gas emission level over the entire building life cycle, $Eges_{max}$, and with a level of greenhouse gas emissions related to construction products and equipment, $Eges_{max,PCE}$. $Eges <= Eges_{max}$ & $Eges_{PCE} <= Eges_{PCEmax}$. Two levels make up the scale of performance levels relating to greenhouse gas emissions: the level "Carbon 1" accessible to all construction modes and the level "Carbon 2" valuing the best performing operations.

***Bâtiment Bas Carbone* (BBCA)** is a low-carbon building whose label is a reference to the low-energy building label. Officially registered in 2015, the purpose of BBCA is to certify low-carbon emission projects (Le Breton & Aggeri, 2018).

CONCLUSION

This chapter has identified relevant concepts, tools and technologies and defined them so that the rest of the manuscript will be more understandable. In the chapter 2, we will provide the overall state of the art related to the context of our thesis.

CHAPTER 2

The state of the art

INTRODUCTION

This chapter presents the current State Of The Art in relation with the context of our thesis. First, we describe the state of the art of interoperability in BIM. Moving on, Section 2.2 introduces Semantic Web technologies in construction industry. In Section 2.3, we discuss the integration of BIM and LCA for sustainable construction. Then, the Section 2.4 describes our research process. The latter contents, among other elements, objectives and research questions.

2.1 INTEROPERABILITY IN BIM

Interoperability is the ability of diverse entities to work together, using the parts or equipment of each other, to achieve a common goal, regardless of their divergences. Ide & Pustejovsky (2010) define it as a measure of the degree of that ability. The need for interoperability faces many obstacles, namely interoperability barriers.

Archimède & Vallespir (2017) distinguish three kinds of interoperability barriers: conceptual, technological and organizational barriers. Conceptual barriers concern only information problems like their representation at a high level of abstraction or the level of programming. They are about syntactic and semantic incompatibilities of the information to be exchanged. That is the difference of data formats, the ambiguity of meaning or understanding. Syntactic and semantic incompatibilities hinder interoperability at a very high level since it corrupts the ability of two or more systems or elements to exchange information and to use the information that has been exchanged. Technological barriers concern IT problems, which is related to the use of computers or ICT[1] to communicate and exchange information. They are about incompatibility of IT architecture and platforms, infrastructure, operating systems, database technologies, etc. Thus, technological barriers can be divided into Communication barriers, content barriers and infrastructure barriers. Organizational barriers concern human problems like responsibility, authority or organizational structure and management. They can concern database management, security policy, etc.

By considering these definitions, we conclude that AEC domain is mainly faced with conceptual and technological interoperability barriers.

In AEC domain, conceptual interoperability barriers consist in the variation of information representation, syntactically and semantically, between different actors. For instance, IFC files do not have the same structure depending on the software that generates them. Resolve this will procure advantage of the structuration of the data exchange and the codification of the data including vocabulary, so that the receiving systems will be able to interpret it.

Technological interoperability barriers in AEC consist in the lack of agreement, in terms of ICT, to tackle key issues of the domain (Muller et al., 2015; Tchouanguem Djuedja J.F., 2019). For instance, there is neither standardise ontologies to hold the semantics of the building, nor standardise ontologies for construction products at the time of writing.

When tackling the importance of interoperability in BIM, over-viewing challenges and listing existing solutions is an important step. The next paragraph 2.1.1 highlights the need of interoperability in BIM.

[1] Information and Communication Technologies

2.1.1 The need of interoperability in BIM

The building is a complex object, thus, the issue of interoperability is even more present in the building sector. The diversity of actors involved and the very long life cycle of the building decrease the ability to solve encountered problems. In fact, the consensus is difficult to reach and to claim it would be almost too ambitious although not impossible. Interoperability is an important issue in complex area such as architectural precast facades (Sacks R. & Y., 2010). The erection of that kind of facade required close collaboration among various actors: architects, precast fabricators, structural engineers and general contractors; it is a good candidate for the usage of interoperability in AEC domain.

When BIM systems are interoperable, different construction stakeholders working in the same office or on different sites can share information about the different phases of a project. A simple case would be when, in the same office, the structural engineer and the architect work separately on a 3D model of the same building. The two models must be combined to plan the project in a tool such as Navisworks. Also, all updates by each actor must be report to the global 3D model along the life cycle of the building. To be done, this work needs an appropriate interoperability at all levels.

Interoperability in BIM is an important need for it serves for rules checking (Pauwels et al., 2011) and energy performance assessment (EPA) (Choi et al., 2016). The latter demonstrates how interoperability can improve BIM-based EPAs. For rules checking in AEC domain, interoperability can improve communication between BIM software and rule checking environments. To improve BIM-based EPAs, Choi et al. (2016) develop a material library and an openBIM-based energy analysis software, validated by a case study. Interoperability here takes advantage of the fact that more than 70% of the information needed for the building energy analysis is already contained in BIM data. In the construction industry, EPA should be boosted through a perfect interoperability between BIM data and energy simulation models. Moreover, ensure the interoperability of BIM can be useful to check the compliance of buildings with HQE (Haute Qualité Environnementale) and BREEAM (Building Research Establishment Environmental Assessment Method) standards, or with the E + C- (Energie + Carbone -) label.

2.1.2 Review of the state of art on interoperability challenges in BIM

Despite the benefits of interoperability, there exist factors hindering its full potential in sharing construction project information. Steel et al. (2012) mention four levels of interoperability in BIM while focusing on IFC-based interoperability:

- File level is the ability of two tools to successfully exchange files;
- Syntax level is the ability of two tools to successfully parse those files without errors;
- Visualization level is the ability of two tools to faithfully visualize model being exchanged;
- Semantic level is the ability of two tools to come to a common understanding of the meaning of a model being exchanged.

Considered those levels, Steel et al. (2012) enumerate few interoperability issues such as:

- Issue 1: Very large size of the models being used. It results in failures when generating 2D drawings or rendering in 3D, and the inability to load models because of number of objects or memory consumption restrictions.

- Issue 2: The use and reuse of geometries which results in inappropriate position of objects when tools are changed.
- Issue 3: Alternative Visualizations which modify model appearance in different tools, depending on the objectives in play.
- Issue 4: A loose approach to the use of object identifiers which causes difficulties of versioning in case of the merging of models from different actors for example.
- Issue 5: Coverage of a BIM-based language by implementing tools, or coverage of the domain by the intended language.
- Issue 6: Variation of levels of parameterisation support by different tools.

The existing literature on interoperability challenges in BIM suggests diverse trends. Firstly, there is a challenge in capturing and translating knowledge from experts into a BIM software (Kensek & Delcambre, 2015). The perspective of an architecture engineer who enter information is not the same as the perspective of an energy analyst. For example, a beam could be viewed as a volume of concrete and a mass of steel reinforcing bars by the architecture side while it would be a thermal bridge for the energy designer. Secondly, sometimes, in one specialty, different kinds of information from BIM must be considering. For instance, in construction: facility management, architectural and geometric BIM information are needed. This involves various software systems to undertake the construction of a building. Thirdly, the fact that data evolve following the different phases of a construction project is a challenge. Data present in building models evolve as the project progresses. Thus, design and construction models are rarely the same, especially in very complex projects (Kensek & Delcambre, 2015). At the beginning of the building design, the model contains only an assembly of 3D objects. For example, for a concrete wall, all starts with a 3D drawing. Then, progressively, other information are added: its cost, its role, the time dimension, etc. These additions take place one after the other throughout the life cycle of the building, and will allowing at certain moments to evaluate the environmental impact of this wall and then to ideally make the necessary adjustments before the construction. The problem is that the information needed for an efficient assessment is not necessarily available at the right moment. Furthermore, if the used information change, the assessment becomes incorrect.

The key question is what are solutions to interoperability challenges with regards to BIM for sustainable construction? To answer this question, it is imperative to learn from previous studies. The next section attempts to give some answers.

2.1.3 Existing solutions for interoperability issues in BIM

Some solutions have been proposed to solve interoperability issues in building domain. Grilo & Jardim-Goncalves (2010) cite some of them. Among others, there are international/regional or national standards, labels, ontologies, models, and so on.

Afsari et al. (2017) propose to use the JavaScript Object Notation (JSON) format to introduce ifcJSON schema and its data content. ifcJSON is the first implementation of IFC data model based on JSON data exchange format, and it would be an alternative to ifcXML. From a standardized JSON schema, valid ifcJSON documents produced is to be used for Web-based data transfer and to improve interoperability of cloud-based BIM applications. Unfortunately, there is currently no tools capable of previewing geometric data contained in ifcJSON.

Hu et al. (2016) address interoperability challenge between architectural and structural models and among multiple structural analysis models. They have proposed the prototyping of IFC-based Unified Information Model (UIM) and various algorithms in two software system architectures: Client/Server (Unitive-BIM) and Browser/Server (Web-BIM) platforms. IFC-based UIM is a data model, implemented as a central data server. For model display, the Web-BIM platform is based on WebGL (GL means Graphic Library) whilst Unitive-BIM is based on OpenGL.

Pauwels et al. (2017b) bring AEC together with Semantic Web technologies by proposing an OWL ontology for IFC file format. IFC is as a matter of fact, the main file format used in building industry nowadays. Establishing that the Semantic Web technologies were likely to overcome the interoperability problems in building field, they took advantage of the production of ifcOWL ontology by the BuildingSmart's Linked Data Working Group (LDWG) team, for their proposal (Pauwels, 2016). The BuildingSmart's LDWG team has relied on earlier work (Pauwels et al., 2015) to "convert the IFC schema into an OWL ontology and to convert IFC STEP Physical Files (SPF) into Resource Description Framework (RDF) graphs that follow the ifcOWL ontology".

S. (2014) has introduced a way to combine Web of Data (WoD) and IFC technologies. The need for interoperability increases as BIM model data evolves. Within BIM, S. (2014) distinguishes type-level interoperability from instance-level interoperability. Type-level interoperability concerns the common interpretation that different tools share for the same object whilst instance-level interoperability concerns the types of entities representing different aspects of the same real-world object. The Web of building data consists of three spheres corresponding to the degree of complexity needed for a proper exchange of data between actors. The deepest sphere corresponds to the part of WoD represented according to the IFC ontology: it is the Web-based BIM, where all datasets can be manipulated with same tools. The outermost and the middle spheres respectively represent the Web (interlinked resources using URIs, HTTP and HTML/XML) and the WoD (structural data in RDF).

Introduced by de Farias et al. (2016), FOWLA means Federate Architecture for OWL Ontology and aims to improve interoperability of BIM at data level. This rule-based federated architecture aims to leverage Semantic Web technologies for interoperability between the AEC/FM (Facility Management) and other ontologies, to solve data structure heterogeneity issues.

BuildingSmart (2016) describe some International/National or Regional standards as an attempt to solve interoperability issues in BIM. They are constituted of:

- TC184/SC4 by ISO within WG3 (Product modelling), the T22: Building construction group.
- ISO 10303-STEP, part 225 called: "Application Protocol (AP): Building Elements Using Explicit Shape Representation"
- IFC developed by IAI(Industry Alliance for Interoperability) to improve interoperability of applications from different software vendors. The latter has adopted ISO EXPRESS language to describe its models.

In fact, some classes in IFC have been defined according to ISO 10303 standard and its derivatives: ISO 10303-46, ISO/CD 10303-46:1992, ISO10303-42 and ISO/CD 10303-42:1992. IFC also facilitates exchange between already used format in BIM, such as rvt or rfa, through translation processes. Another attempt cited in Grilo

& Jardim-Goncalves (2010) is the BIM standardization to link GIS to AEC by two means: by linking IAI/IFC to GIS or by linking GIS-BIM-CAD. For energy simulations and for predicting current energy demand and carbon emissions, Arayici et al. ARAYICI Y. et al. (2018) have proposed an interoperability specification to promote early collaboration.

The Table 2.1 separates above-mentioned solutions conceptual or technological interoperability barriers in BIM.

Table 2.1: Categories of interoperability barriers

Approaches that address technological barriers	Approaches that address conceptual barriers
Related to the use of ICT	enable semantic & syntactic compatibilities
International standards (BuildingSmart, 2016):"TC184/SC4", "ISO10303-STEP part 225", IFC	IfcJSON (Afsari et al., 2017)
Interoperability specification (ARAYICI Y. et al., 2018)	ifcOWL (Pauwels et al., 2017b)
GIS-BIM-CAD (Grilo & Jardim-Goncalves, 2010)	FOWLA (de Farias et al., 2016)
	Copying IFC schema to OWL and IFC SPF to RDF (Pauwels et al., 2015)
	IFC-based UIM (Hu et al., 2016)

2.1.4 Discussions

BIM needs a reliable environment to enable flexible information exchange between all project actors in order to achieve its aim in building domain. The so-called interoperability is a key to ensure a sustainable construction of buildings, that means a construction that is environmentally friendly, cost-effective and comfortable for users. As BIM wants to evolve, trying to respond to the increasing needs of various actors, the interoperability challenges increase. The major interoperability problems identified in the BIM are the translation or coverage issues, the variety of tools dealing with different kind of information and the very large size models. There is also the evolution of data all along the life cycle of the building and the alternative visualization issue. International standards such as TC184/SC4, ISO10303-STEP or IFC were amongst first attempts to deal with interoperability in BIM. They were completed by interoperability framework and then the construction of many BIM-based ontologies or data model implementation like ifcOWl, FOWLA, IFC-based UIM or ifcJSON. Considering the state of the art review, it is sure that all these efforts are significant. Yet, they are insufficient to ensure interoperability in the field of AEC and particularly for sustainable construction. Interoperability issues are rarely encountered in the BIM model itself, but rather in the capacity of the model to handle necessary data in order to pursue a particular goal. In fact, most recent solutions promote instance-level interoperability and encourage the usage of BIM-based ontologies. However, owing to the lack of coverage of the domain or because of the quality of ontology construction, some of the solutions proposed need improvements. One improvement could be the enhancing of a widely used BIM-based ontology or the creation of a new ontologies that are usable on various platforms. Most of the identified solutions attempted to address conceptual interoperability barriers and suggest that ontologies are best positioned to solve both the problems related to semantics and those related to the syntax of the information exchanged between stakeholders of a construction project. At this time, several research approaches have covered the subject of Semantic Web technologies in general and more specifically ontologies in construction industry (Pauwels et al., 2017b, 2015; de Farias et al., 2016). This will be the subject of the next section.

2.2 SEMANTIC WEB TECHNOLOGIES IN CONSTRUCTION INDUSTRY

2.2.1 Approaches using building-based ontologies

Various ontologies have been proposed since the 2000s in the domain of building construction to overcome issues that are encountered there. Among them are COBIeOWL, DOGONT, IfcOWL and IfcWOD.

2.2.1.1 IFC

Born from an initiative of the IAI (International Alliance for Interoperability), later renamed "buildingSMART", the Industry Foundation Classes (IFC) comprise an object-oriented format based on the STEP standard (buildingSMART International Ltd., 2017). IFC is governed also by the ISO 16739 (ISO 16739:2016) standard and employs the EXPRESS-G language (Wix, 2015), for its representation. The IFC data model allows users and software vendors to uniformly represent building data according to the specifications of the IFC schema. IFC defines semantics, relations, and properties of data as follows:

- 'Semantics' refers to the identity of the data;
- 'Relations' define how the data are linked using referrals within the IFC data file;
- 'Properties' include geometric properties (for example dimensions of the object), physical properties (nature and use of the material), and qualitative data pertaining to the object (unit price, manufacturer, and so on).

In IFC, data are encoded in three formats (buildingSMART International Ltd., 2013):

- IFC: based on the STEP physical file structure defined by the ISO 10303-21 standard;
- ifcXML: the XML translation of IFC defined by the ISO 10303-28 standard;
- ifcZIP: a compressed archives format of involving either of the previous two formats, potentially including additional content such as PDF files, images, and so forth .

The most recent version of IFC is the Industry Foundation Classes Version 4 - Addendum 2 (IFC4 Add2) (buildingSMART International Ltd., 2017).

Multiple authors have applied the IFC EXPRESS schema to construct ontologies with the goal of improving interoperability in the built environment: Pauwels (2014a); Pauwels & Terkaj (2016); Pauwels et al. (2017b), etc. Unfortunately, this has led to the creation of a variety of partially non-interoperable ontologies, including ifcOWL (Pauwels, 2014a), but also ifcWoD (de Farias et al., 2015) and FOWLA (de Farias et al., 2016). This growth in the number of BIM-based ontologies also stems from the fact that, as we shall see, most of them have only limited expectations as concerns what an ontology can achieve.

2.2.1.2 IfcOWL and IfcWOD

IfcOWL Starting out from the first version of ifcOWL (Beetz et al., 2009), Pauwels (2014a) and Pauwels et al. (2017b) propose significant enhancements. Semantic Web technologies were then brought to the AEC domain in Pauwels & Van Deursen (2012), which proposed an ontology for the IFC resting on converting the EXPRESS schema into an OWL ontology. By connecting IFC schema and underlying any of the BIM environments, they proposed an AEC description framework: an architectural information modelling (AIM) framework. AIM consists in a Semantic Web graph containing all kinds of building information, including geometric and material information, architectural intents, etc. IFC is nowadays the main file format used in the AEC industry for BIM-compliant projects.

ifcOWL is an ontology for the building domain whose main purpose is to support the conversion of IFC instance files into equivalent RDF files. It provides an OWL representation for IFC schema and IFC data that have been made available in the form of a labelled oriented graph (RDF). ifcOWL is the most robust implementation of an IFC-based ontology ifcOWL. Its most recent version was created in 2016 and proposed by the W3C Linked Building Data Community Group in the same year (Pauwels, 2014a).

There are four main benefits for BIM to be obtained with Semantic Web technologies along the lines of ifcOWL, as identified by Pauwels et al. (2017b) , Pauwels & Terkaj (2016) and Pauwels et al. (2011). First, they can improve information exchange in the construction industry. Second, they can enrich the value of BIM by enabling data integration and complex queries across multiple data sources. Finally, they can make it possible to infer additional information from RDF and OWL data through use of OWL reasoners. The problem, however, is that ifcOWL fails to achieve these benefits both because of its poor structure and because of the lack of definitions for its terms.

IfcWOD The IFC Web of Data Ontology (ifcWoD) was introduced by de Farias et al. (2015), with The rationale that the existing version of ifcOWL (IFC2X3.owl) does not fully exploit the capabilities of OWL. To rectify the resulting problems, de Farias et al. (2015) translate certain attributes in the IFC schema into object properties rather than into OWL classes and instances.

The resulting ifcWoD ontology is useful for certain BIM purposes. Thus, it facilitates the writing of requests, optimizes their execution, and reduces the redundancy of the data by increasing the capacity of what is derivable from reasoning engines. However, these features are not sufficient to improve interoperability with other ontologies in the same field, since ifcWOD inherits the weaknesses of the version of ifcOWL which forms its basis. In order for ifcWoD to address interoperability issues, therefore, ifcOWL would itself need to be improved first.

2.2.1.3 DOGONT

The Domotic OSGi Gateway ONTology (DOGONT) is an ontology created by Dario Bonino in 2008 to support domotic (which is to say: home automation) environments (Bonino & Corno, 2008). DOGONT consists of four classes: BuildingThing, BuildingEnvironment, State, and Functionality as described in Table 2.2.

Table 2.2: DOGONT classes

Class	Role
BuildingThing	models available things, either controllable or not
BuildingEnvironment	models the places where things are located
State	models the stable configurations that controllable things can assume
Functionality	models what controllable things can do

However, even though DOGONT was very well developed with few errors according to OOPS! (2016) and Parrot (2017), it has hardly been used in any dataset.

Furthermore, DOGONT focuses on the operational phase of construction and does not integrate with other phases of the building life cycle such as design, maintenance or demolition. DOGONT suffers also (like almost all ontologies) from the lack of association with a top-level ontology in a way that promotes interoperability with other ontologies using the same top-level ontologies.

2.2.1.4 COBie and COBieOWL

Introduced by Farias et al. (2015), COBieOWL is an OWL ontology based on the Construction Operations Building Information Exchange (COBie). COBie standard has been created under the auspices of the National Building Information Modelling Standard (NBIMS) (East, 2007). It serves the publication of building information models that are focused on delivering asset data, as distinct from geometric information. COBie provides data in STEP or in other static formats such as those used by standard spreadsheets. It thus lacks logical formalism and semantic features. COBieOWL was developed to fill this gap.

Like Industry Foundation Classes (IFC) itself and its related ontologies, COBie-OWL should enhance BIM interoperability; but its coverage domain is exclusively that of the COBie standard. Which means that COBie is limited in the benefits it can bring to the wider AEC domain. Furthermore, COBie was made only for contractors, builders, designers and facility managers (East, 2007), rather than for all actors involved in the construction project. Lastly, the majority of BIM software in the market is still unable to read and/or generate COBie files.

2.2.1.5 FOWLA

The Federated Architecture for OWL Ontology (FOWLA) was proposed by de Farias et al. (2016) to improve the interoperability of BIM at the level of data. FOWLA is a rule-based federated architecture aiming to leverage Semantic Web technologies to support interoperability and to resolve data structure heterogeneity issues between different AEC/FM (Facility Management) ontologies.

FOWLA brings two main advantages. First, it allows users to write queries by combining terms from ifcOWL, COBieOWL and ifcWoD. Second, it builds on a rule engine which allows new alignment rules to be inferred. For example, transitivity is used to automatically deduce that COBieOWL is aligned with ifcWoD which is in turn is aligned with ifcOWL. Unfortunately, leveraging heterogeneity at vocabulary level, which is to say between the terms used in these different ontologies, is not sufficient to allow semantic interoperability between actors in the AEC industry. For in practice, stakeholders often use the same term but associate with it completely different semantics. de Farias et al. (2016) which is still the only paper on FOWLA lacks details as to how this issue will be rectified.

2.2.1.6 Other building-based ontologies concerns: analysis, modularisation, serialization, simplification and optimisation

Ontological analysis. Borgo et al. (2015, 2014) have made some reservations concerning the conversion of the IFC standard into an OWL ontology. To respond to the need of an in depth ontological analysis of the conversion of IFC standard into OWL, they propose to increase the correct understanding and use of the standard while ensuring logical coherence, ontological soundness and conceptual clarity, focusing on IFC type/occurrence distinction. In Borgo et al. (2015), they underline the lack of common conceptualization of the terms used by various actors across different communities and the lack of formal representations threaten the quality of process and product modelling as well as the effective sharing of data between the stakeholders. Also, they claim that the research community is focusing more on transcriptions of standards into ontology languages than on their translations in ontology. To overcome underlined issues, they propose a deep study of the IFC standard by looking at an existing OWL version of IFC, by highlighting the implicit assumptions and by applying ontological analysis to discuss how to grasp the type/occurrence distinction in IFC.

Optimisation of the applicability of ifcOWL. In the same note, in order to optimize the applicability of ifcOWL, Terkaj & Šojić (2015) propose to revise the conversion pattern of IFC EXPRESS schema into OWL ontology. According to previous studies, there were three main conversion criteria. They keep the first two and replace the third one by their own criteria: Analysis of rules in the IFC schema and ensuing conversion into the ifcOWL to support the direct instantiation of the ontology and guarantee its consistency. First, they improve conversion pattern of IFC EXPRESS schema into OWL ontology for instance by adding axioms. Then, they implement additions to the conversion pattern into a software tool.

Simplification of ifcOWL Pauwels & Roxin (2016) propose to simplify ifcOWL building data in order to address to specific industrial use cases. They introduce the implementation of a simplification process through a declarative manner. Their first proposal is the release of geometrical and (re)presentation data. Secondly, they proposed the unwrapping of wrapped data types. The first proposal brings a reduction of the triple number and the file size also. The second contribution allows safe and uniform conversion of EXPRESS and IFC-SPF constructs into OWL and RDF respectively. They based their third and fourth addition on the ifcWOD proposal from de Farias et al. (2015). However, the reduction of triples brought by this proposal might reduce the expressiveness of ifcOWL. Also, it is difficult to understand their choice using an old IFC schema (IFC2X3_TC1) for the sample case while there exist a more recent version of the IFC schema (IFC4).

Modularisation of ifcOWL. While de Farias et al. (2016) propose a federated architecture to solve some data heterogeneity in AEC domain (FOWLA), TERKAJ & PAUWELS (2017) propose a modularisation of ifcOWL to overcome its rigidity. TERKAJ & PAUWELS (2017) investigate the possibility to split ifcOWL into multiple modules while avoiding issues of circular imports after modularisation and reciprocal dependencies. Among many strategies, they choose to do a modularisation by contents because IFC standard was developed in a modular way. Instead of modularize the already existing monolithic ontology ifcOWL, their algorithm converts an EXPRESS schema to a modular OWL ontology. The proposed algorithm aims to find the best way of implementing a given input modularisation by minimizing the number of direct import relations between modules. However, the proposed approach could hinder semantic interoperability in building domain because the automatic conversion of an EXPRESS schema to an OWL ontology produces the lack of precise definitions of some concepts.

Serialization. To tackle the very large size and the complexity of ifcOWL ontology, Pauwels et al. (2017a) propose a serialization of geometric aggregated data into alternatives. By using both IFC2x3 and IFC4 sample files, they aim to find a more efficient representation of geometry and to maintain the geometry decomposition instead of reducing geometry to one simple triangulated mesh. While taking advantage of modularisation of ifcOWL, the proposed approach still needs a trade-off between semantic precision and computational efficiency.

Acknowledge the overlapping of the purposes of IFC with the goals of some applications, Pauwels & Terkaj (2016) propose some criteria that would be required to build a recommendable ifcOWL ontology such as:

- The ifcOWL ontology must be in OWL2 DL;
- The ifcOWL ontology should match the original EXPRESS schema as closely as possible;
- The ifcOWL ontology primarily aims at supporting the conversion of IFC instance file into equivalent RDF file. In fact, their aim is not to create RDF graphs from scratch, using only ifcOWL ontology.

The problem with the closeness of the ifcOWL to the original EXPRESS schema is that it makes it more difficult to handle and even understand. Due to the complexity of the EXPRESS schema, the resulting ontology is also complex, that does not facilitate its use in applications or by experts even if it enables the instantiation of each IFC file into an equivalent RDF file. Thus, what is the need of a prodigious ontology if it cannot be used in the targeted area? Exploring other Semantic Web technologies such as Linked Data could, without necessarily producing a prodigious ontology, but contribute to achieving this ultimate goal.

2.2.2 Approaches integrating BIM and linked data: Linked Building Data (LBD)

Linked Building Data (LBD) To the best of our knowledge, LBD is the bridge between Linked Data and AEC industry since it enables the representation of building data into RDF graphs (Pauwels, 2014b). In other words, LBD is the result of the use of Semantic Web technologies for the structuring of building data into a set of RDF graphs that can be shared between stakeholders, involved tools and through the internet. LBD is making use of a set of available vocabularies like Building Topology Ontology called BOT (W3C-LBD-CG, 2018a), Properties set definition ontology called Props (W3C-LBD-CG, 2018b), Product ontology called PRODUCT (Schema.org, 2018), with the aim of gathering, using in tools and sharing of building data. Recently it has emerged many implementations related to LBD.

Pauwels (2014b) discuss about the lack of semantic interoperability among information systems in Building Life Cycle (BLC) and the inadequacy between features provided by information systems and functionalities expected by end users. LBD was here suggested as a possible approach to address the highlighted issues.

Terkaj et al. (2017) propose an ontology-based modelling to address heterogeneity in AEC/FM industry. They underline that the overlapping of a multitude of ontologies in the scope of AEC/FM tends to inhibit the general adoption of Semantic Web technologies throughout the industry. Thus, they implement a BACS (Building Automation Control Systems) ontology in alignment with existing ontologies; namely SAREF, DOGONT, ifcOWL, etc. The implemented ontology is modular and enables the integration of data from BIM and Building Automation System (BAS). By federating many existing ontologies in the scope of the AEC/FM industry, the BACS ontology proposed carries with itself the drawbacks of each of them.

Building Topology Ontology (BOT) and other building-based ontologies The challenge of managing the complex structure of the IFC EXPRESS schema has been a major obstacle to success in developing building ontologies. The W3C LBD community group has developed an ontology for the AEC domain: BOT (Rasmussen et al., 2017b; Terkaj et al., 2017). It defines BOT as a minimal OWL DL ontology for describing the core topological concepts of a building; that means BOT includes relationships between subcomponents of a building. They have also provided a set of best practices for the treatment of building data on the web and the building topology ontology (BOT), which was immediately aligned with ifcOWL, DOGONT, as well as with ontologies for the geospatial and sensor domains.

BOT tends to be a solid foundation for the use of Semantic Web technologies in the scope of the AEC/FM area. In addition, its respect for W3C rules of non-redundancy and simplicity for easier maintenance is a plus and brings building experts into a confident environment for wide adoption of related technologies. Furthermore, because of the existing links and the extensions that can be made between BOT and various domain-specific ontologies, BOT could stand as a reliable exchange platform between experts in building area. Rasmussen et al. (2017a) follow the preceding work by giving more details about the implementation of BOT and recent developments.

Using three building-based ontologies: BOT (building topology), PRODUCT (classification of building elements) and PROPS (building-related properties), Bonduel et al. (2018) convert building data into RDF graphs so-called LBD. Comparatively to previous implementations of building data into RDF graphs (Pauwels & Roxin, 2016; Beetz et al., 2009; TERKAJ & PAUWELS, 2017), data are not in one monolithic and complex graph which relies on the drawbacks imposed by the usage of IFC standard. Graphs are rather separated into building elements (according to BOT), products (according to PRODUCT ontology) and property set definition (according to PROPS).

Upcoming ontologies of this initiative (covering products, geometry, and the properties of building elements) will also attempt to be aligned to ifcOWL (W3C, 2018; W3C-LBD-CG, 2019). We believe that an improvement of the underlying ifcOWL structure, as well as of its ability to promote interoperability is essential to provide more semantic enrichment and accuracy of those ontologies.

2.2.3 Approaches using other Semantic Web technologies from the Semantic Web stack: SPARQL, SWRL, JSON, XML, etc.

Since BLC includes a huge diversity of domains and disciplines as architecture, project management and many others, there is a serious need to address interoperability issues faced by involved actors when they exchange information. Looking forward to avoid existing solutions, Costa & Sicilia (2017) address this issue by operating on data generated several transformations like mapping between input and target ontologies using SPARQL. Thus, this method is subject to limitations of each particular domain-based format generated. For instance, semantic limitations of IFC as stated by Bonduel et al. (2018) will be engaged in the mapping process.

Pauwels et al. (2011) investigate the possibility to use both an information description language and a rule language stemming from the Semantic Web field as a possible enhancement of IFC for building performance checking. They state some limitations of interoperabilities workflow with IFC and suggest that the adoption of Semantic Web technologies can enable the usage of declarative approach in the development of rule checking environments, arguing that such approach conserves the significant efforts put into the design and specification of IFC.

Abanda et al. (2013) investigate the development and trends of Semantic Web technologies in built environment. In addition, they underline research challenges, potential future development and research directions that can be followed. Furthermore, they highlighted the need of real reusable, easy and freely available Semantic Web applications in the built environment domain. Acknowledging the need for building models to better support complex semantic functionalities and the need for model designers to consider semantic information constructs, Grzybek et al. (2014) discuss semantic models with relation to determining the most suitable information structure. Then, they propose a set of questions to be used during the models feasibility study. In addition, with the goal of helping assess the most suitable method for managing semantics in the built environment, they propose some guidelines.

Abanda et al. (2017) address the issue that causes cost estimation process to be time-consuming and error-prone by proposing an ontology based on New Rules of Measurement (NRM). The proposed ontology is to be used for cost estimation during tendering stages and is implemented using methontology. Afsari et al. (2017) propose to use the JSON format to introduce ifcJSON schema and its data content as detailed in paragraph 2.1.3.

2.2.4 Discussions

Other well known computer science technologies have been experienced to tackle issues in construction industry . For instance, Vanlande et al. (2008) address the issue of the management and the communication of the data generated by building activity by proposing a design and management method that is an extension of the BIM technology. Their method uses IFC files to facilitate the sharing process for a better qualification and validation of data. There are other attempts to use computer science technologies without semantic Web in the construction industry such as:

- Abanda F. H. (2015); Shadram F. et al. (2016)
- Chong & Wang (2016); Chen et al. (2017)
- Sacks et al. (2018); Koo & Shin (2018); MIRARCHI & PAVAN (2019).

Among the variety of approaches, We want to take advantage on the one hand of the ontologies for the semantic depth that they bring and on the other hand Linked Data, for its ability to facilitate the instantiation of the ontologies implemented and their use in software tools of the construction industry.

2.3 SUSTAINABLE CONSTRUCTION: THE ROLE OF BIM AND LIFE CYCLE ASSESSMENT (LCA)

Antón & Diaz (2014) propose to combine two major tools: BIM and LCA in order to achieve sustainability of construction by satisfying both environmental, social and economic criteria. BIM and LCA have already proved, separately, their added value in the target goal. Thus, their main contribution rests on the opportunity to combine different tools whilst raising both pros and cons depending on the combination approach. Moreover, they argue that the overall scope of BIM could be increased by creating synergies with other methodologies as LCA.

2.3.1 Integration of BIM & LCA

The idea of integrating BIM and LCA is quite new and emerged under various titles: BIM-LCA integration (Najjar et al., 2017), BIM and sustainability, (Ansah et al., 2019), BIM and BSA(Building Sustainability Assessment) (Carvalho et al., 2019), LCA and BIM (Rezaei et al., 2019), LCA of buildings in BIM environments (Bueno & Fabricio, 2018; Nizam et al., 2018), etc. the most popular being BIM-LCA integration. In fact, there have been many initiatives of BIM-LCA in the last decades but most of them falls in the three past years: a raise of 90% according to Santos et al. (2019a).

2.3.1.1 Goals

Main goals of BIM-LCA integration studies are:

1. Carry out LCA using BIM at early design stages and throughout the BLC;
2. Enable the BIM to act as a data repository for supporting an automatic/semi-automatic LCA;
3. Enable the visualization of LCA results in BIM tools;
4. Empower the decision-making process in order to achieve more efficient, cost-effective, and sustainable design standards at early stages of designing construction projects (Najjar et al., 2017);
5. Empower semantics both in BIM and in LCA data and tools.

2.3.1.2 Challenges & locks

The state of the art highlights three groups of challenges in BIM-LCA integration:

1. **Challenges for researchers**
    - Lack of research that considers all dimensions of sustainability: environmental, social and economic (Santos et al., 2019a).

- Need to simplify LCA methods application by reducing and optimizing data acquisition (Soust-Verdaguer et al., 2017).
- Insufficiency of methodological details and the need for a systematically defined framework of BIM and LCA (Najjar et al., 2017).
- Need of new methodologies to incorporate LCA into the building design and construction processes (Bueno & Fabricio, 2018).
- Need of flexibility of information sharing between BIM and LCA tools.

2. **Challenges for software developers**

- Interoperability problems between BIM and sustainability tools in general and between BIM and LCA tools in particular (Soust-Verdaguer et al., 2017; Santos et al., 2019a).
- Need to assist in the integration;
- Need for future developments with the aim of improve and standardize integration of BIM-LCA;
- Need to improve data exchange between BIM and LCA (Soust-Verdaguer et al., 2017).
- Interoperability problems between BIM tools and sustainability tools;
- Lack of ontologies across the fields of sustainable construction;
- Lack of standards and public impulses for the adoption of BIM within a sustainable construction industry;
- Lack of BIM libraries with semantic-rich objects. (Santos et al., 2019a).
- Lack of semantic information within BIM models (Santos et al., 2019b).

- Lack of alignment both in terms of nomenclature and in terms of detail level between the BIM material database and LCA tools;
- Lack of an automatic data extractor from BIM to LCA (Rezaei et al., 2019).
- Disconnection between building LCA tools for early and late design stages (Cavalliere et al., 2019).

3. **Challenges for experts and users**

- Need to facilitate the scope of the application of the LCA method into the AEC sector (Soust-Verdaguer et al., 2017) and allow a more complete assessment during the BLC.
- Gap between the extracted BIM parameters and the LCA data requirements (Cavalliere et al., 2018).
- Gap between extracted BIM data and existing data provided by common LCA databases (Dupuis et al., 2017).
- Need to optimize BSA through BIM (Carvalho et al., 2019).
- Lack of information in the LOD 100 stage in the BIM model that entails the lack of integration of BIM and LCA in the early building design stage;
- Lack of information on materials at early design stages of the buildings (Rezaei et al., 2019).
- Lack of data in BIM models in order to perform a whole LCA analysis (Dupuis et al., 2017).
- Need to know and understand the processes involved during the life cycle of the building (Soust-Verdaguer et al., 2017).

2.3.1.3 Existing approaches and trends

Some works simply review existing approaches, highlight needs and propose recommendations for the future of the research (Soust-Verdaguer et al., 2017; Santos et al., 2019a; Ansah et al., 2019). Trends in integration of BIM-LCA can be divided in two groups:

1. **Approaches that use BIM data to perform LCA in LCA tools.**

   Dupuis et al. (2017) propose a method to automatically perform LCA calculations early by introducing a novel data layer and format. In their process, the authors divide the LCA model in two parts: (a) generate the process tree structure necessary to perform the LCA and (b) Complete the LCA model to perform the LCA at early design stages. Focusing on performing LCA in design and construction stages of the BLC or during the whole BLC, Cavalliere et al. (2019) propose a framework to use LCA as a decision-making support tool regarding the embodied environmental impacts of a building during all phases of the design process. The fact that they are mixing LCA databases that must have the same background data sound unrealistic because of the heterogeneity of LCA databases.

2. **Approaches that use BIM data to perform LCA in native BIM tools with or without the development of a BIM plugin.**

   Cavalliere et al. (2018) identify and encode extracted BIM parameters to perform the LCA of buildings in BIM environments. In addition, Nizam et al. (2018) propose a framework to estimate the embodied energy content within the native BIM environment, which makes things a lot easier. A prototype of their tool has been implemented to estimate the material embodied, transportation and construction energy. Moreover, Santos et al. (2019b) introduce a BIM-LCA/LCC (Life Cycle Costing) framework by developing an IDM (Information Delivery Manual) and MVD (Model View Definition) using the IFC schema, for the integration and exchange of information within a BIM-based environment. They identify durability, density and EPD LCA results as the information required for any BIM objects in order to conduct the complete LCA analysis at LOD 300 stage and above. Using material data to perform LCA in BIM, Rezaei et al. (2019) choose to assign a probability function to each material to manage information uncertainty in the early design stage.

2.3.2 Discussions

Between the variety of existing approaches to integrate BIM and LCA, the main goal is to able to perform the LCA at the building at early design stages of the BLC. Different level of LCA are considered: screening, simplified, streamlined and complete LCA studies (Santos et al., 2019b). Screening LCA is recommended for an initial assessment of the environmental impacts of buildings or products. Similar to screening LCA, simplified LCA is recommended at more advance stages with more data. In the streamlined LCA, experts select the most suitable boundaries and environmental categories for their study (ACADEMY, 2008). The complete LCA corresponds to the framework described in ISO 14040 standard and covers the entire life cycle of buildings or products. Some approaches focus on performing the LCA either in BIM environment (Cavalliere et al., 2018, 2019; Carvalho et al., 2019; Najjar et al., 2017; Bueno & Fabricio, 2018; Nizam et al., 2018; Santos et al., 2019b; Rezaei et al., 2019) by sometimes using BIM-integrated plugin or in LCA tools (Dupuis et al., 2017).

Some authors have highlight the lack of semantic-rich objects in BIM (Santos et al., 2019a). However, none have propose to tackle the following research question: how to take advantage of Semantic Web technologies in order to improve the way LCA is integrated to BIM to perform the LCA of the building throughout the BLC? In our thesis, we address challenges in the three above-mentionned groups namely the need of new methodologies to incorporate LCA into the building design and construction processes, the need to improve data exchange between BIM and LCA and the lack of information on materials at early design stages of the buildings. To ensure the applicability of our methodology, it is closer to ones that use BIM data to perform LCA in native BIM tool with the development of a plugin.

2.4 RESEARCH PROCESS

This section presents our research process in the context of the MINDOC project. First, we have implemented a questionnaire to understand the context of MINDOC in relation to the State of the Art. Then, we present the problem. Next, we highlight our goals and raise the research questions. Finally, we introduce methodology and orientations for this work.

2.4.1 The questionnaire

A questionnaire[2] has been carried out to draw us closer to building industry experts and learn about the realities they face on a day-to-day basis in sharing information to ensure the sustainability of infrastructure being implemented. A building project is divided into ten stages from sketch to demolition or refurbishment (De Vigan, 2013):

[2] https://forms.gle/6Mz8Fuu4Rj1idNm86

1. **Sketch**: Design stage during which the prime contractor proposes overall solutions, reflecting the major elements of the project. He makes a brief representation of the whole project.

2. **Preliminary Draft Summary**: The design stage during which the project is refined, in order to get an idea of its general composition, to imagine the interior volumes and appearance, to propose technical arrangements and to propose a timetable and a budget. This step is a prerequisite for the establishment of a final project and execution plans.

3. **Preliminary Final Draft**: Design stage during which various elements of the project are fixed: surfaces, plans, sections, facades, dimensions and aspects, construction principles, materials and technical equipment, cost estimation in separate lots.

4. **Project (PRO)**: Design stage which makes it possible to specify the conditions for the use of all materials, the supply and discharge routes for fluids and to determine the overall time and cost of the work.

5. **Execution (EXE)**: Set of studies allowing the realization of the work by establishing the synthesis plans, the detailed specifications by batch, and to make the technical consistency of the documents provided by the companies.

6. **Construction**: Concretization of an infrastructure project.

7. **Commissioning**: Process of assuring that all systems and components of a building are designed, installed, tested, operated, and maintained according to the operational requirements of the owner or final client. (Wu & Issa, 2012).

8. **Use**: Use of the building.

9. **Operation and maintenance**: Upkeep and conservation work in good operational condition.

10. **Demolition or refurbishment**: refurbishment is the restoration of a new appearance to a building or bringing it to a condition similar to the original one, after its degradation by time, weather, wear and tear, etc.

While going beyond literature and look at concrete cases, our questionnaire aimed at collecting expert opinions on information exchange issues that they face while using BIM and trying to perform LCA studies of buildings. It has been answered by 26 experts. Among other results, it was found that our proposals would be the most suitable in the preliminary final draft (52.9%) and the preliminary draft (47.1%) phases of the Building Life Cycle (BLC). The questionnaire has been mostly answer by experts which have a very common use of BIM in their work (61.9%), most of them being BIM managers (40%). It also appears that BIM is more used in early phases of the BLC, including preliminary draft, the project phase (PRO) and the implementation phase (EXE). Revit software or more generally Autodesk suite appears to be the most used software by BIM experts. In addition, four main obstacles appear to prevent the development of BIM on a larger scale:

1. Lack of interoperability with construction industry software

2. High technology infrastructure requirement (cost, memory size, processor speed, etc.)

3. Technological backwardness of the construction industry software

4. Complexity of BIM

In the seldom collaborative projects, the BIM model is supplemented with data from construction industry software (thermal, mechanical, costing, labor, planning, etc.) 45% of the time. For example, engineers who would benefit from the supplementation of the BIM model with external data, do not yet integrate it as a need in their exploitation of the digital model. This happens because of many factors such as: (i) many professions are immature on the subject, and (ii) the optimization in the use of BIM is not yet on the agenda.

Moreover, it appears that half of the experts use several complementary databases of building materials during a construction project, because only one is not enough. Within this variety of databases, they face some heterogeneity issues. Four environmental assessment methods appear to be the most used in France:

- *Haute Qualité Environnementale* (HQE)
- BRE Environmental Assessment Method (BREEAM[3])
- Energy +/ Carbon - label (E+/C-)
- *Bâtiment Bas Carbone* (BBCA)

The questionnaire tends not only to confirm what came out of the literature but also to highlight more practical issues encountered by experts in the building industry. To overcome the highlighted issues, many tools are needed. Among others, there are BIM, Semantic Web technologies, Life Cycle Assessment(LCA), etc.

[3]BRE= Building Research Establishment

2.4.2 The identified problematic

In view of the context, the problem statement of the MINDOC project can be divided in three groups:

1. **issues that are linked to the construction project itself**:
    - Existence of different types of information to be exchanged between several actors using various tools
    - The actor's point of view is a serious issue. It occurs when two entities do not share the same point of view on the same object. For example, when the architect sees a specific beam as a simple volume of concrete and a mass of steel, the energy engineer sees the same beam as a thermal bridge.
2. **Issues that occur only between software tools** that were partly described in paragraph 2.1.2. These are mainly interoperability issues.
3. **Issues link to characteristics of environmental databases**
    - Heterogeneity of environmental databases: differences of functional units, size differences, differences in accordance with regional or international standards, methodological differences used for LCA, etc.
    - Difficulty in effectively evaluating the building to be built, to ensure compliance with the multitude of standards and labels in force.

In the context of this thesis, we try to address only some issues linked to the construction project itself and the heterogeneity of environmental databases.

2.4.3 Goals

With regards to identified issues in building sector relating to information exchange for ensuring a high level of sustainability, there are still several issues. Firstly, our aim is to study how information exchange is made within experts during a building lifecycle in order to figure out interoperability gaps. Then, we will fill some of the encountered gaps by mean of formalization of building information. Combined with the formalization of environmental data on construction products, the latter will enable the introduction of product environmental data at an early stages of the building lifecycle. Finally, our aim is to promote the effective use of BIM for the assessment of environmental performance throughout the building lifecycle by integrating and referencing environmental data on construction products into usual BIM tools. Finally, we will deepen semantics in created ontologies by the enhancement of an existing ontology.

2.4.4 Research questions

The research questions that we try to address in this work can be summarized in the following:

1. How can environmental data be available in a flexible way at early stages of building project? Can we improve the exchange of building information throughout the building project?

2. How to take advantage of Semantic Web technologies in order to improve the way LCA is integrated to BIM to perform the LCA of the building throughout the BLC?

3. What are solutions to interoperability challenges with regards to BIM for sus-

tainable construction? If implementing ontologies was a step on the way to the solution,what is the need of a prodigious ontology if it cannot be used in the targeted area?

CONCLUSION

This chapter has provided a state of the art on interoperability in BIM, the use of Semantic Web technologies in construction industry and the integration of BIM-LCA to pursue sustainable construction of buildings. In addition, we have detailed a research process to identify problems, specify goals and highlight research questions that we will try to address.

Considering the State of the Art, we are interested in the integration of BIM-LCA by taking advantage of building-based ontologies and LCA databases. The latter directs us towards the enhancing of a widely used BIM-based ontology and the use of high-level ontology.

CHAPTER 3

Integration of multiple EPD databases & Including environmental data in building data

INTRODUCTION

To enhance the sustainability of building, involved actors should be able to access and share not only information about the building but also data about products and especially their environmental assessment. Moreover, among others, the assessment of the environmental impact of the building is one of the most important studies to be conducted and that implies accurate information available and shared between involved actors. The latter study relies on the accessibility of environmental construction product data.

In recent years, in addition to their functional performances or their cost, the environmental quality of the building products has become a selection criterion. For any building construction project, the experts in the field need to choose the construction products before or during the execution phase. However, they are heterogeneities between environmental databases such as: differences of functional units, size differences, differences in accordance with regional or international standards, methodological differences used for LCA, etc. In addition, some of them contain only a few construction products. Among several approaches that have been proposed to achieve that, Semantic Web technologies stand out from the crowd by their capabilities to share data and enhance interoperability between the most heterogeneous systems. Moreover, there are a number of problems that still do not have accomplished solutions. BIM data and Semantic Web technologies have been widely but separately used to try to overcome it with some success elsewhere.

This chapter presents a review and classification of environmental databases from France, UK or Europe. An effective choice of the suitable construction product among the variety of environmental databases is a critical aspect to tackle the issue of sustainability in building domain. Among other issues highlighted by Pauwels (2014b), this chapter addresses the issue of associating Semantic Web technologies with environmental databases to increase the flexibility needed to perform and assess the building's environmental impact throughout its life cycle. By implementing our approach based on RDF graphs, this part of our work provides insights on how Linked Building Data (LBD) can be combined to environmental data in the form of RDF graphs in order to improve the environmental impact assessment of a building throughout its life cycle.

The next Section holds the related work (3.1). It is followed by the research method (3.2), which has 2 major parts: classification criteria for LCA databases and ranking of LCA databases. Then, our methodology on integrating multiple EPD is introduced in 3.3. Finally, making environmental data available as Linked Data constitutes the Section 3.4.

3.1 RELATED WORK

3.1.1 State of the art on comparative LCA studies

Many studies have tried to compare or analyse lots of LCA databases and particularly for construction materials.

Lasvaux et al. (2015) assess and compare two existing LCA databases: ecoInvent and INIES. Their aim is to emerge numerical and methodological differences. For that, they compare 28 building materials using environmental impact indicators of the EN 15804 standard calculated on ecoInvent and EPD LCI. First, there are deviations of different magnitudes depending on the environmental impact indicators and the building materials. Some indicators are systematically different between EPD and data from ecoInvent, which are generic. Furthermore, some building materials show systematic differences for all Life Cycle Impact Assessment (LCIA) methods. Lasvaux et al. (2015) claim that differences mainly depend on the type of the environmental indicator and that the impacts are controlled by a limited number of materials; i.e that the final result depends on a limited number of materials.

Moreover, Martínez-Rocamora et al. (2016) conduct a literature review of LCA databases, specifically for construction materials. Their aim is to provide a starting point for the selection of LCA databases for construction materials, by facilitating choices between the wide varieties existing. Those LCA databases are divided into three groups: European, American and National Databases. Those groups contain following databases: ecoInvent, GaBi Database, ELCD Database 3.1, Athena Database, base Carbone, ProBas, etc. They proposed six main features to compare LCA databases: scope, completeness, transparency, comprehensiveness, update and licence but their study focuses on three aspects: completeness, transparency and comprehensiveness. They finally found transparency to be the decisive feature in their comparison. They recommend traceability, comprehensiveness and methodology as key features when comparing two construction materials.

In addition, Takano et al. (2014) make a comparison of five LCA databases, based on three reference buildings. Among the databases, there are Gabi, IBO, ecoInvent and Synergia. Their aim was to show numerical and methodological differences between diverse buildings LCA. Each database is presented and they are compared to each other based on Greenhouse gas (GHG) emissions values in the material production phase of the reference buildings. They found that databases showed similar trends in the assessment results and the same order of magnitude differences between the reference buildings. Furthermore, the plethora of data elements prosecutes numerical differences between building LCA.

However, one LCA database is rarely sufficient to carry out the LCA study of a building throughout its lifecycle. This last observation brings out the need to integrate multiple LCA databases in order to facilitate their exploitation by AEC experts. Many technologies have been experienced for the integration of databases in general, but Semantic Web ones stand out by their abilities and thus retain our attention.

3.1.2 Integration of databases using ontologies

Many approaches have been tried to integrate databases. Among them, there are Ontology-Based Data Access/Integration - OBDA/I from Wache et al. (2001), On-Top based on OBDA and KARMA from Knoblock et al. (2012).

KARMA is better suited for big data integration with semantic (Knoblock & Szekely, 2013), and particularly to solve problems of big data variety (Knoblock & Szekely, 2015), or to discover the semantic relations between various data sources as Taheriyan et al. (2016) did.

Many approaches exist for OBDA/I: single, multiple or hybrid Ontology approaches. As present by Calvanese & Xiao (2018), the OBDA/I opposes the explicit construction of RDF graphs from heterogeneous data sources to rely on a declarative mapping of data sources to ontology while maintaining the RDF graph virtual. The aim is to avoid the drawbacks link to data duplication, freshness, and potential conflicts with data management policies and privacy requirements. Xiao et al.

(2018) propose framework of ontology-based data access by introducing a semantic paradigm for providing a convenient and user-friendly access to relational data repositories. Others propose to enrich with provenance semirings to reconstruct why a tuple occurs in the answer of a query (Calvanese et al., 2019). (Calvanese et al., 2015) introduce the Ontop framework to enable a transparent querying of various relational databases using SPARQL requests. The Ontop framework comprises four layers: (i) Inputs composed of OWL 2 QL ontologies, R2RML mappings, relational databases and SPARQL queries. (ii) Ontop Core that includes the Ontop SPARQL Query Answering Engine (QUEST) and various API and parsers. (iii) API Layer that comprises the OWL API and the Sesame Storage Inference Layer API. (iv) Application Layer that includes Protege, Optique Platform and the Sesame Workbench & SPARQL Endpoint. Built for relational databases, Ontop can be adapted for various and recent data sources like JSON or XML.

Despite the widespread adoption of these database integration technologies using ontologies, they are specifically designed either relational, big or legacy data sources. However, the abstract layer of OBDA/I for querying can be reused because it provides the user with a transparent way to query heterogeneous data sources. The latter, so-called Ontop by the designers, requires adaptation to suit EPD databases (Calvanese et al., 2015).

3.1.3 Integration of environmental data and BIM data

Antón & Diaz (2014) have highlighted some pros and cons of integrating LCA in a BIM environment. Two approaches were suggested. Based on extracting direct project data from the BIM model to perform LCA, the first one allows evaluation of the complete construction during its entire life cycle. The second approach is suitable for selecting materials and elements since it is based on the inclusion of LCA-related information in the features of the various BIM objects.

The methodology chosen in our thesis is closer to the second approach of Díaz & Antön (2014). It is focusing on EPD databases that contain construction product and are usable in France. In France, sanitary information have been added to EPD to form what is called "*Fiche de Déclaration Environnementale et sanitaire*" (FDES) or "Environmental and Health Declaration Sheet".

3.1.4 Linked Building Data(LBD): an essential tool to include environmental data in building information

LBD is the result of the use of web semantic technologies for the structuring of building data into a set of RDF graphs that can be shared between stakeholders, involved tools and through the internet. LBD is making use of a set of available vocabularies like Building Topology ontology called "BOT" (W3C-LBD-CG, 2018a), Properties set definition ontology called "Props" (W3C-LBD-CG, 2018b), Product ontology called "PRODUCT" (Schema.org, 2018), and many others, with the aim of gathering, using in tools and sharing of building data. Recently many implementations related to LBD have emerged (Terkaj et al., 2017; Bonduel et al., 2018; Rasmussen et al., 2017a).

Using three building-based ontologies: BOT, PRODUCT and PROPS, Bonduel et al. (2018) convert building data into RDF graphs so-called LBD. Comparatively to previous implementations of building data into RDF graphs (Beetz et al., 2009; Terkaj & Šojić, 2015; Pauwels et al., 2017a), data are not in one monolithic and complex graph which relies on the drawbacks imposed by the usage of IFC standard. Graphs are rather separated into building elements (according to BOT), products (according to PRODUCT ontology) and property set definition (according to PROPS). Taking advantage of the opportunity of separating product data from others building data (properties and building elements), environmental RDF data can now be easily integrated to it without increasing the complexity of data querying or browsing (Bonduel et al., 2018).

Since BLC includes a huge diversity of domains and disciplines such as architecture, project management and many others, there is a serious need to address interoperability issues faced by involved actors when they exchange information. Looking forward to avoid existing solutions, Costa & Sicilia (2017) address this issue by operating on data generated (by BIM applications and other tools like energy, acoustics, economics, etc.) several transformations like mapping between input and target ontologies using SPARQL. Thus, this method is subject to limitations of each particular domain-based format generated. For instance, semantic limitations of IFC as stated by Bonduel et al. Bonduel et al. (2018) will be engaged in the mapping process.

Focused on material data, Schwartz et al. (2016) propose the integration of EPD data in RDF format. Undertaking the definition of instances of EPD data manually is laborious, makes it subject to human errors and is likely impossible if there is a large amount of data. Moreover, relying on IFC export-import capabilities of the BIM tool used makes their methodology subject the limitations of those capabilities.

3.2 SELECTING ENVIRONMENTAL DATABASES

3.2.1 Classification criteria

According to researches made and literature on building material databases and LCA databases (Martínez-Rocamora et al., 2016), we propose 16 classification criteria merged into 8 groups, which can be used to review them, as shown in Figure 3.1.

1. **Scope** includes not only the categories of materials studied but also their geographical coverage. It means the place where materials were manufactured.
    - The geographical area covered
    - The number of materials covered or the size of the database
    - The number of categories of materials covered
    - The different environmental indicators and their units
2. **Completeness** responds to the question: is each variation of material covered by its category?
3. **Transparency** What is the methodology used? Is it explained? Is a literature reference associated with it? What are the boundaries of the study? What are the flows considered? etc.
    - Traceability
    - Methodology
4. **Comprehensiveness** measures the level of details and the integrity of information provided for each material.

- The availability of documentation.
- The degree of confidence of data enter by vendors, are they standardized?

5. **Update** measures the difference between the last update of the database and the date at which it is used for an assessment process.

    - The length of life of the information recorded in the base
    - The update frequency and policy

6. **License** indicates whether a paid license is necessary or not in other to access the databases. It means the license type (fee/free), is there an academic license? Commercial or open databases?

7. **Interoperability capacity** measures the ability of the database to interact with different entities and expresses its openness. It responds to questions like: in which formats are the data available? Is the database compliant with most used software on the market? In how many languages are the information in the database available? Is this information compliant with up-to-date national/international standards? How many users does the database have?

    - The data format(s) in which data is available: web, pdf, sheets, text, xml, etc.
    - The compatibility/availability of the database with/in most used software
    - The number of users
    - The languages use in the database: are they available in English language or not?

- The standards with which information are compliant

8. **Eco-friendliness** of an LCA database specifies the percentage of eco-friendly or biosourced materials that it contains.

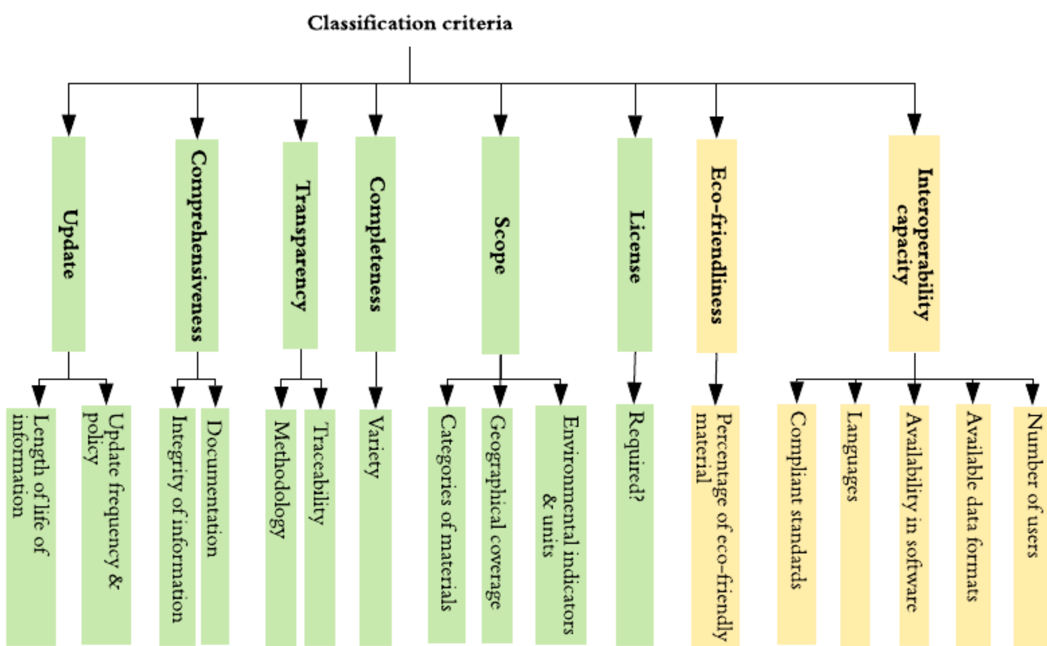

Figure 3.1: Classification criteria. Classification criteria are divided in 8 groups to categorize LCA databases

The Figure 3.1 summarizes classification criteria arrangements. When studying a particular building materials database or LCA database, the above criteria are important to our objective. Before presenting a non-exhaustive list of databases on building materials, it should be recalled that our objective is to identify and then coordinate all existing LCA databases, with the aim of promoting the use of environmentally friendly materials and then encouraging sustainable construction. Following the previous elucidated criteria, we will focus on ten databases to explore them. Among others, they are: INIES, ÖKOBAUDAT, IBU-EPD and EPD database.

3.2.2 Ranking of EPD

We have classified some LCA databases referring to the presented criteria.

3.2.2.1 INIES

INIES is a French national reference database of environmental and health declarations (HQE-GBC, 2018). INIES contains construction products, equipments and services with the aim of evaluating their work performance. INIES has many stakeholders in which CSTB [1] acts as the database administrator, HQE [2] serves as owner-manager since 2011, AFNOR [3] manages the independent third-party audit program. In addition, DHUP (Directorate General of Urban Planning, Housing and Construction) and AIMCC [4] respectively chair its supervisory board and its technical committee. INIES is only available in French language and only used in France by the moment. It is a free access database but unfortunately conditioned by the holding of a Microsoft Silverlight license. There is a web service to provide access to digitized data, but it needs fee payment. For each product inside the database, image or pdf files are available to provide more information about it.

Contents description For building construction, INIES has 2096 entries divided into 3 categories: construction services, construction products and electronical/-electrical equipment. Building is the only family in INIES catalogue. For each category, it provides detailed data for environmental declaration per each report-

[1] *Centre Scientifique et Technique du Bâtiment*
[2] *Haute Qualité Environnementale*
[3] *Association Française de NORmalisation*
[4] *Association des industries de matériaux, produits, composants et équipements pour la construction*

ing body. For each product, they give four important types of information: general information, functional unit, environmental indicators, retrievable documents and sometimes health and comfort. The environmental indicators comprise environmental impacts, resources consumption, wastes and outgoing flow. In Documents field, a default or normal EPD is usually found, and sometimes an audit certificate, images and so forth. That normal EPD is compliant with the NF EN 15804+A1 standard and its national addendum XP P01-064/CN.

Limits In the absence of specific environmental data available for a product or a service, INIES provides a default generic environmental data followed by a warning concerning the usage of that default environmental value. While browsing INIES database, we notice it contains relatively poor information about biosourced materials such as those made with hemp, wood, straw or clay. For example, for thermal insulation from the inside, 14 of the 246 references are biosourced.

The table 3.1 summarizes characteristics of INIES.

3.2.2.2 *Gabi*

Made by thinkstep (2018), GaBi database is an LCA database spanning most industries including building construction. **Contents description** GaBi database contains over 12000 ready-to-use LCI (Life Cycle Inventories) profiles based on primary industry data. Developed over 20 years ago in over 20 countries, GaBi database is still evolving today. That gave to it an up-to-date content and a compliance with three standards: ISO 14044, ISO 14064 and ISO 14025. It dedicates its fourteenth extension to 3124 processes on construction materials. For each process, it provides process information (location, reference year...), modelling and validation, administrative information, inputs and outputs.

Table 3.1: INIES

Scope	Geographical coverage	France
	Categories of materials	Construction services (45), construction products (1457) and electronical/-electrical equipment (916)
	Environmental indicators & units	4 groups containing 26 indicators: environmental impacts, consumption of resources, wastes, outgoing flows.
Completeness	variety	2418 entries
Transparency	Traceability	available
	Methodology	Available in each LCI (Cradle-to-gate)
Comprehensiveness	Documentation	available
	Integrity of information	AFNOR
Update	Update frequency & policy	weekly
	Length of life of information	5 years
License	Required	yes
Interoperability capability	Available data formats	Images, Pdf & through webservices
	Availability in software	Elodie Marsault (2017)
	Languages	French
	Number of users	
	Compliant standards	NF EN 15804+A1
XP P01-064/CN		
Eco-friendliness	percentage of eco-friendly material	5%

Limits GaBi database has the advantage to be available for 20 countries. Furthermore, the Gabi Data Search, a research engine, provides the opportunity to find a specific process or material within the database by specifying one to five criteria. However, the entire data can only be accessed via Gabi Software. The table 3.2 summarizes value of classification criteria for Gabi.

Table 3.2: Gabi

Scope	Geographical coverage	Over 20 countries - worldwide
	Categories of materials	15
	Environmental indicators & units	
Completeness	variety	3124 processes on construction materials
Transparency	Traceability	available
	Methodology	Cradle-to-gate
Comprehensiveness	Documentation	available
	Integrity of information	Verified by Derka
Update	Update frequency & policy	Annual
	Length of life of information	6 years
License	Required	yes
Interoperability capability	Available data formats	Pdf & XML
	Availability in software	GaBi Software Suite
	Languages	English
	Number of users	
	Compliant standards	ISO 14044, ISO 14064 and ISO 14025
Eco-friendliness	percentage of eco-friendly material	N.A

3.2.2.3 Quartz database

Constructed by Google, Healthy Building Network, FLUX, thinkstep, and other companies, Quartz Common Product database is a building material database, which aims to:

- Inform all stakeholders in the whole life cycle of a building for data transparency between manufacturers and project team;
- Create helpful decision-making tools for project teams. That means, from analysts, researchers, consumers, software developers, tool providers to project team and manufacturers, all are concerned by the availability of high quality and reliable data on building construction materials.

Contents description For any of 102 products in quartz database, there are:

- A description
- The general composition of the product
- The impurities contained
- The health profile: aggregation of potential health hazard
- The environmental profile: LCIA results of an ISO 14044 compliant
- LCA
- Some sources: mainly documents and literature referenced.

Limits Too few products are described in this database, compared to the amount of products descriptions needed to almost ensure sustainability in building construction through a right choice of materials and construction products.

3.2.2.4 ecoInvent

Being a Switzerland LCI database, ecoInvent provides documented process data for many products in order to inform users about their environmental impact, covering in many countries, a lot of sectors such as construction materials, manufacturing, agriculture and energy. ecoInvent 3.4 is the latest version and it is based on all previous version of the database. It was released on October 2017. It is integrated into SimaPro 8 and GaBi 5 software Martínez-Rocamora et al. (2016). Furthermore, ecoInvent is compliant with studies and assessments based on ISO 14040 and 14044. General information on ecoInvent are summarized in Table 3.3.

Contents description In its latest version, over 1000 updated datasets were added in diverse sectors, including some for building and refractory materials. ecoInvent provides over 13300 LCI datasets.

Limits ecoInvent is a commercial LCI database which does not deliver enough of information for external users.

3.2.2.5 Bath ICE

The Sustainable Energy Research Team (SERT) of the University of Bath has set up the Inventory of Carbon and Energy (ICE), namely Bath ICE. The first version of bath ICE was edited in 2005 and the latest one in 2011 Hammond et al. (2008); PROTOCOL (2019).

Contents description The data used for the construction of Bath ICE database comes from Academic research, industry statistics, government publications and other LCA databases. It also includes Athena Institute International, Boustead Model, BRE, FEFCO (GREENHOUSE GAS PROTOCOL). Bath ICE database is made of one Excel file, which contains over 34 spreadsheets. It provides profiles

Table 3.3: ecoInvent 3.4

Scope	Geographical coverage	Europe
	Categories of materials	construction materials, manufacturing, agriculture and energy
	Environmental indicators & units	
Completeness	Variety	+13300 LCI datasets
Transparency	Traceability	available under license
	Methodology	Cradle-to-Gate
Comprehensiveness	Documentation	Available outside
	Integrity of information	N.A
Update	Update frequency & policy	4th October 2017
	Length of life of information	years
License	Required	yes
Interoperability capability	Available data formats	N.A
	Availability in software	SimaPro 8 and GaBi 5
	Languages	English
	Number of users	N.A
	Compliant standards	ISO 14040 and 14044
Eco-friendliness	Percentage of eco-friendly material	N.A

of more than two hundred building materials, which belong to 34 different categories. For each material, the embodied energy, the total CO2 and the total CO2e (CO2 equivalent: used to allow other greenhouse gases to be expressed in terms of C02 based on their relative global warning potentialToolkit (2012)) are evaluated. General information about Bath ICE are presented in Table 3.4.

Table 3.4: Bath ICE

Scope	Geographical coverage	UK
	Categories of materials	34
	Environmental indicators & units	Embodied energy, the total CO_2
the total CO_2e		
Completeness	Variety	+400
Transparency	Traceability	original sources available
	Methodology	Cradle-to-Gate; Cradle-to-Grave; Cradle-to-Site
Comprehensiveness	Documentation	Available
	Integrity of information	Ensured
Update	Update frequency & policy	2011
	Length of life of information	Information provided for each material
License	Required	No
Interoperability capability	Available data formats	HTML (web) access to Excel or PDF file
	Availability in software	None
	Languages	English
	Number of users	
	Compliant standards	ISO 14040/44
Eco-friendliness	Percentage of eco-friendly material	N.A

Limits The main advantage of this database is that it is mainly a building-related database and is available free of charge in an Excel file. However, it is compatible only with ISO 14040/44 standard.

3.2.2.6 Base Carbone

Managed by ADEME, Base Carbone is French database which aims to enable carbon emissions bookkeeping. Data contains categories of products for France and its territories ADEME (2018a) ADEME (2018b). However, the usability of the documentation is submitted to the holding of a license. Additional information on Base Carbone is presented in Table 3.5.

3.2.2.7 DIOGEN

Being an open-access database, DIOGEN means *Données d'Impact pour les Ouvrages de GENie Civil* (Peuportier, 2016) and is a product of the AFGC[5]. It is a French LCA database available in terms of downloadable PDF files. Using the same methodology as ecoInvent, DIOGEN is a cradle-to-gate environmental database. It was initially based on the NFP01010 standard but was subsequently adapted to be in line with the EN 15804 standard. DIOGEN provides impacts of production materials used in France for civil engineering.

Contents description The DIOGEN groups approach is to characterize the environmental data and then to decide on its acceptability. It contains 5 categories and 44 materials. For each product, available information is name, description, number of downloads, a downloadable file. Each file contains, for the product being described: confidence index, environmental impacts according to standard NF P01-010, complementary environmental impact, reference, technological assumptions and hypothesis environmental information module. General information on DIOGEN database are summarized in Table 3.6.

Limits The web tool CIOGEN is based on DIOGEN and offers an assessment

[5] *Association Française du Génie Civil*

Table 3.5: Base Carbone

Scope	Geographical coverage	France
	Categories of materials	12
	Environmental indicators & units	Greenhouse gas emission - CO2 kilograms per ton
Completeness	variety	Around 1300 materials
Transparency	Traceability	Not enough
	Methodology	Cradle-to-grave
Comprehensiveness	Documentation	Provided but externally
	Integrity of information	
Update	Update frequency & policy	April 2016
	Length of life of information	3 years
License	Required	No
Interoperability capability	Available data formats	CSV
	Availability in software	None
	Languages	French
	Number of users	
	Compliant standards	
Eco-friendliness	percentage of eco-friendly material	N.A

of the stages of production and construction road bridges according to EN 15804.

3.2.2.8 *Other LCA databases*

In addition to all databases presented above, there is an international system of EPD for a wide range of product categories. However, the amount of data in

Table 3.6: DIOGEN

Scope	Geographical coverage	France
	Categories of materials	5
	Environmental indicators & units	MJ, kg, kg eq. Sb, kg eq. CO2, kg eq. SO2, m3, kg eq. CFC-12, kg eq. C2H4, kg eq. PO43-,l
Completeness	Variety	44
Transparency	Traceability	N.A
	Methodology	Cradle-to-Gate
Comprehensiveness	Documentation	Available
	Integrity of information	Verified by an AFNOR certified auditor
Update	Update frequency & policy	2013
	Length of life of information	No limit
License	Required	Free - subject to registration
Interoperability capability	Available data formats	HTML and PDF file
	Availability in software	CIOGEN
	Languages	French
	Number of users	Users of CIOGEN + others
	Compliant standards	NFP01010 then EN 15804
Eco-friendliness	Percentage of eco-friendly material	N.A

building area is poor. For instance, we have found 11 products and services concerning building and infrastructure category and most of them are about railways, bridges or roads. For construction products category, there are 377 EPD available.

Available in English, and sometimes in Turkish, the EPD database furnish for each product:

- EPD documents in all available languages
- Climate declaration of the product but not for all products
- Product information
- Detailed information like the registration number, the reference Polymerase Chain Reaction (PCR), the geographical space, the body item which carries out the verification, the date of validity, etc.
- Company information

The EPD for each product contains interesting and detailed information about parameters and units used, but also the system boundary (cradle-to-grave, cradle to gate with options, gate-to-gate, etc.) and the impact of the product at each stage of its life.

Other databases were out of the scope of this contribution because their scope and ours do not match: either they do not contain any construction material, they do not cover french or Europe geographical area or they were not available in English. Furthermore, not enough information were found to study some LCA databases, thus, they were not inserted in this study.

3.2.2.9 Ranking of LCA databases

The variation of sources of data on construction materials produces almost incomparable results. A scoring system has been chosen with qualitative scores in order to overcome the latter issue.

The LCA databases We have selected the following databases according to the literature (Lasvaux et al., 2015; Martínez-Rocamora et al., 2016; Takano et al., 2014) and in alignment with our study: INIES (D1), GaBi (D2), Bath ICE (D3), ecoInvent (D4), DIOGEN (D5) and Base Carbone (D6).

The criteria Chose in alignment with the literature (Martínez-Rocamora et al., 2016) and the goal of the study, the criteria are scope (C1), completeness (C2), transparency (C3), comprehensiveness (C4), update (C5), and license (C6). In addition to that, interoperability capacity (C7), and eco-friendliness (C8) were added.

The classification Based on Martínez-Rocamora et al. (2016), the scoring system used in this classification is as follow:

1. ***N.A*** the information is not accessible
2. **-** the criteria is not accomplished in the database
3. **+** the database partially or sometimes fulfilled the criterion
4. **++** the criterion is fulfilled at a low level
5. **+++** the database completely fulfilled the criterion

Based on arrays built for each database, a score was awarded for each criterion or sub-criterion. The average score was retained to the criteria that hold components. The result for all the bases is presented in the Table 3.7.

Table 3.7: Ranking of LCA databases

		INIES	Gabi	Bath ICE	ecoInvent	DIOGEN	Base Carbone
	Criteria	D1	D2	D3	D4	D5	D6
Scope	C1	+++	++	+++	++	++	++
Completeness	C2	+++	+++	++	++	++	++
Transparency	C3	++	+++	+++	+++	+	++
Comprehensiveness	C4	+++	+++	+++	+	+++	+
Update	C5	++	+++	++	++	++	++
License	C6	-	-	-	-	-	-
Interoperability capability	C7	++	++	++	++	++	+
Eco-friendliness	C8	++	N.A	N.A	N.A	N.A	N.A

3.2.2.10 Critical appraisal of inventory databases

The more we have databases, the more we have data to describe a building material. Nevertheless, is that possible to combine or integrate existing data to do so? Are those databases compatible or comparable to each other? Through literature and organizations websites, we have noticed the existence of a huge number of material databases. Most of them have the advantages to contain environmental information compliant with national or international standards like ISO 14001:2004 NSAI IQNet Certified, ISO14044, DIN EN 15804, NF EN 15804+A1, etc. These standards mostly concern environmental metrics and EPD. The current limit in most of the databases is that they are not available for building construction tools; there is no direct connection or format compliance between them. Furthermore, they do not integrate specific eco-friendly and renewable materials. The schema in Figure 3.2 summarizes the methodology applied to end up with this appraisal.

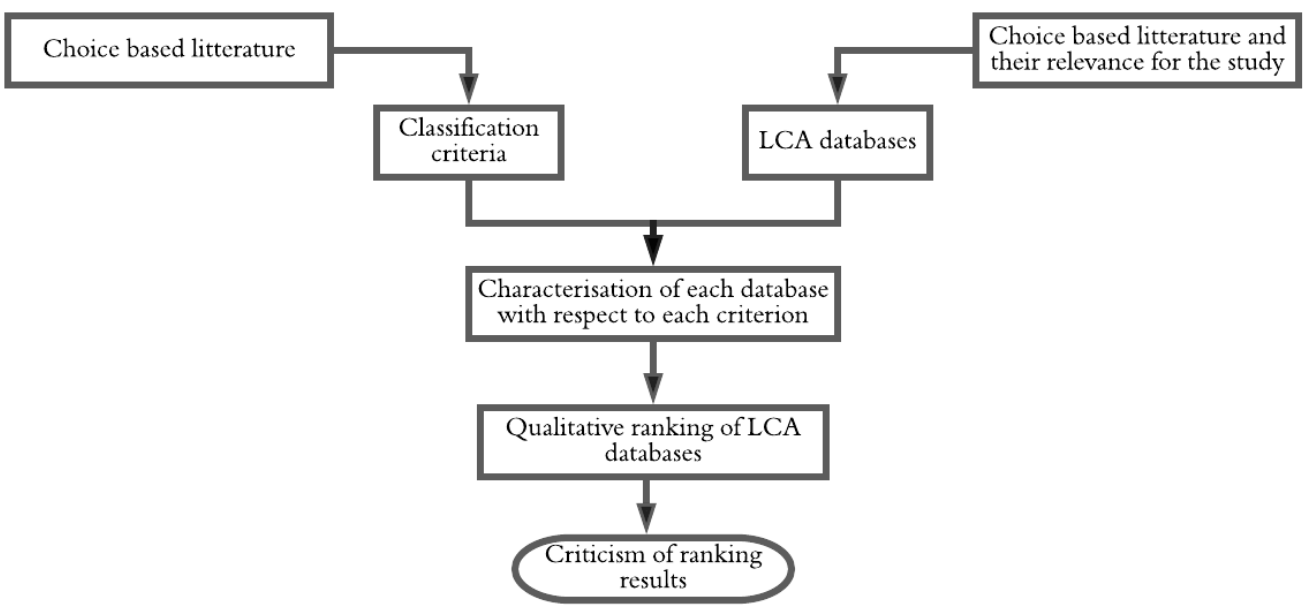

Figure 3.2: The method for critical appraisal of LCA databases.

Since most of the current environmental databases are not yet available in a construction tool, our idea is to implement a framework that integrates many of those databases in order to make it available to most used tools. The latter will also foster the environmental assessment of the whole building throughout its lifecycle.

Referring to the presented classification of LCA databases and the criticism associated, only two of them were retained: INIES and Quartz, as they appear to be more appropriate to fit into our process of integrating them. Despite its limited size, Quartz was associated with our research because of its cost and interoperability capability. Apart from its high cost, Gabi is of great interest for our research because of its characteristics. Its integration with INIES and Quartz will be in the early hours of future works.

3.3 INTEGRATING MULTIPLE EPD

3.3.1 The integration methodology

With the aim of enhancing sustainability in building construction, enhancing the way products are chosen during the life cycle of the building is of critical importance. We make that enhancement through the use of Semantic Web technologies such as RDF, SPARQL, etc.

Pursuing that goal, data were first gathered from EPD databases, then three ontologies were generated. Using the latter, data were translated from their original format, XML and JavaScript Object Notation(JSON) formats, to RDF graphs. To address the issue of accessibility of product and their environmental assessment at the same time by users during the whole BLC and particularly the design phase, we extend an existing BIM tool by adding a plugin to upload products from a triplestore of EPD databases. LDB of each specific building is then generated using our plugin through the user interface(UI) of the BIM tool. The proposed integration methodology is described in Figure 3.3.

3.3.2 Making environmental data available as linked data

In view of their use with building data, environmental data are made available as RDF Linked Data to be further stored into a triplestore. To make environmental data available as RDF graphs, data are first gathered from EPD databases, then using nomenclature data, corresponding ontologies are generated. Nomenclature data contains a classification of construction products. Finally, using generated ontologies, environmental data are translated from their custom formats into RDF graphs. All those functionalities have been developed in one single Java API. The following paragraphs present each step of this process. Inspired by Ontop framework of Calvanese et al. (2015), our global methodology follows a framework called "MINDOC EPD Integration Framework" (MEIF).

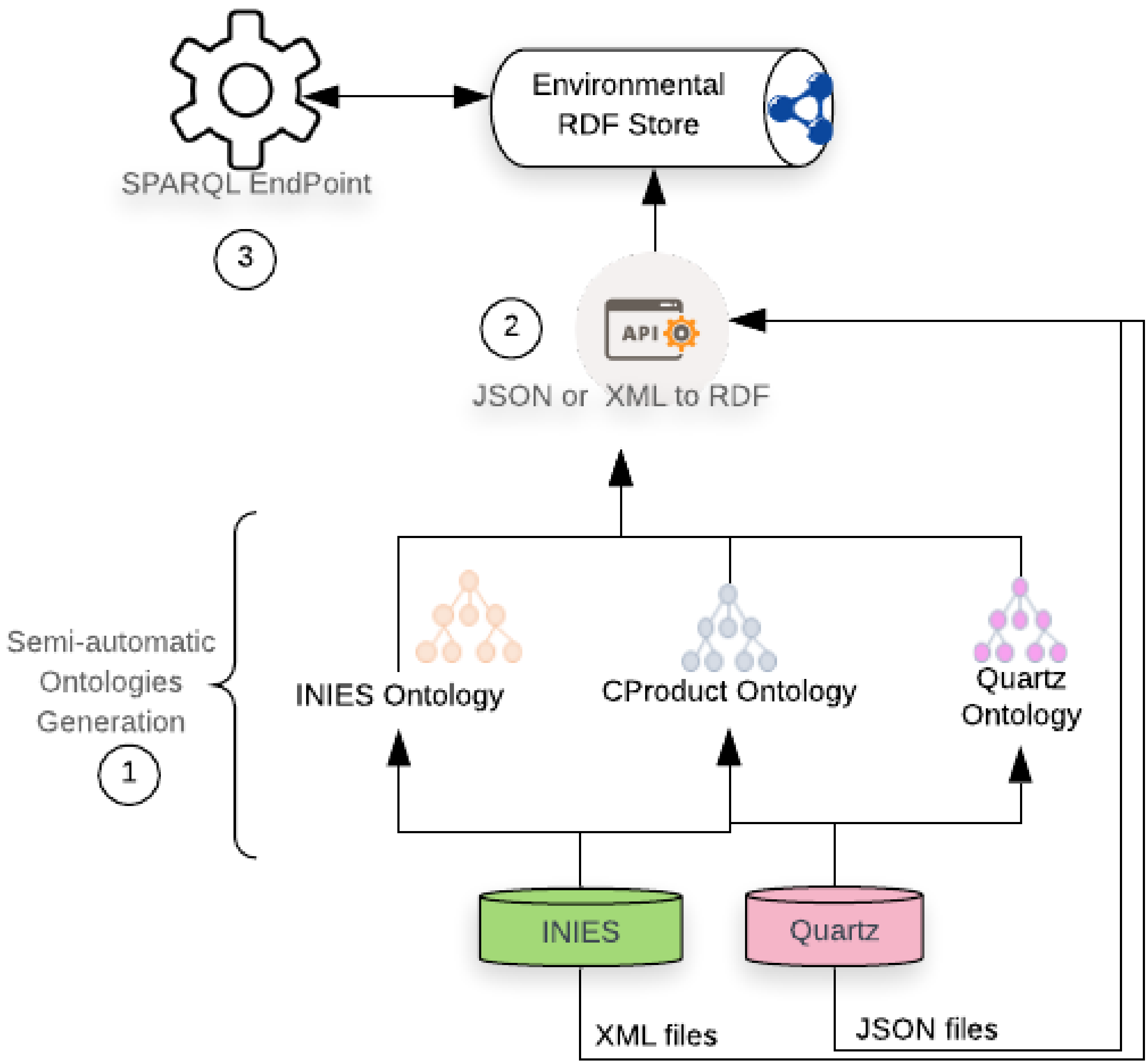

Figure 3.3: The integration methodology.
Using a Java Application Programming Interface (API), ontology derived from environmental data are first semi-automatically generated. Then, environmental data from INIES & Quartz databases are translated from XML or JSON to RDF graphs and stored in a triplestore.

The MEIF is divided in four layers: (i) A data layer that comprises EPD databases. (ii) An API layer that comprises implemented API and SOAP web services queried by the Postman client. Implemented API comprise The XML-RDF API and the JSON-RDF API. (iii) A Core layer that includes the command line editor and the Stardog Server, Jena API and the MINDOC-SDS GENDATA. (iv) An application layer that comprises the MINDOC SPARQL Query Answering, the MINDOC Revit-Plugin, the Revit user interface and reused the DotNetRDF API. The MEIF is depicted in Figure 3.4 whilst the overall method is described in Figure 3.5.

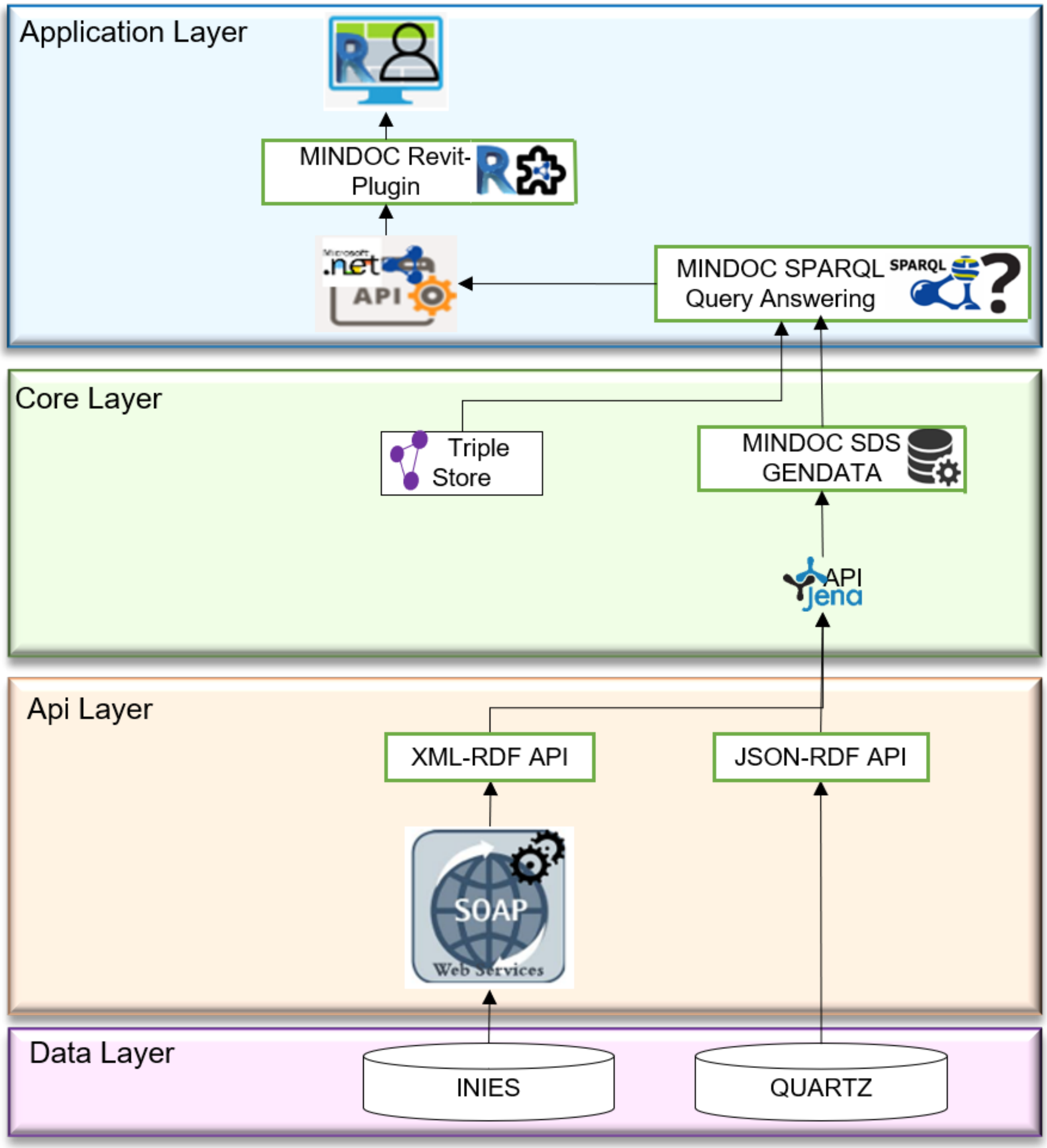

Figure 3.4: The MINDOC EPD Integration Framework (MEIF)

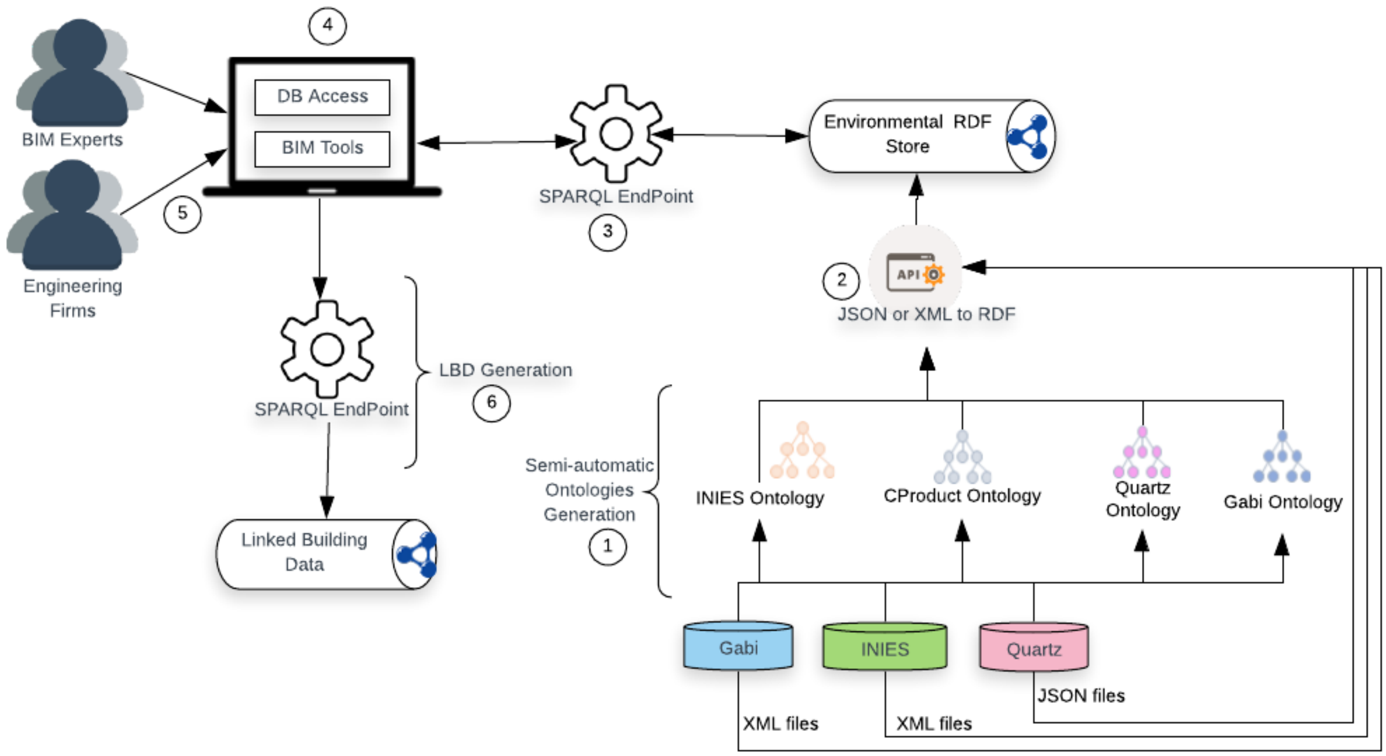

Figure 3.5: The global integration method.
Right side: Using a Java Application Programming Interface (API), ontology derived from environmental data are first generated. Then, environmental data from INIES, Quartz & Gabi databases are translated from XML or JSON to RDF graphs and stored in a triplestore. **Left side:** A plugin is developed and installed in a BIM tool to enable the access to the environmental data. At the end of the modelling phase, users can generate LBD and store them into a triplestore.

3.3.2.1 *Gathering data from EPD databases*

Two EPD databases have been chosen to apply our method: INIES and Quartz.

INIES INIES is the "French national reference database on environmental and health declarations of products, equipment and services for the evaluation of the performance of works" HQE-GBC (2018). It provides Environmental and Sanitary Declaration Sheets (FDES) for construction products. The information in the database is mostly verified by an independent third party in accordance with European regulatory requirements: the NF EN 15804 A1 standard and its French supplement XP P01-0641CN.

An academic license was used to quickly access the INIES web services (IWS) needed to implement the presented method, with extra programming using a free API 2018 Postman (2018). The round trip of sending requests and receiving responses, using Simple Object Access Protocol (SOAP), allows to gather INIES data in the form of XML files; each file containing the response for each sent request. After the login, the *GetNomenclature* request is sent to gather the entire nomenclature tree used in INIES.

The response of the *GetNomenclature* request consists of a collection of Nomenclature items. Each item includes various properties such as id, a name, the id of its parent, and so on. Each item is identified with an id in the INIES database and can have a parent which is another item. "*Bois massif*" is one of the nomenclature item in INIES database. Its XML serialization is presented in Listing 3.1.

Listing 3.1: GetNomenclature response - the 153 Nomenclature Item and its parent

```
<NomenclatureItem>
<NomenclatureItemID>153</NomenclatureItemID>
<NomenclatureItemName>Bois massif</NomenclatureItemName>
<ParentItemID>23</ParentItemID>
<TreeLevel>3</TreeLevel>
<HasChildren>false</HasChildren>
</NomenclatureItem>
```

Quartz Quartz is a Worldwide EPD database. Its data are available for free online, either in a single but not detailed Microsoft Excel Open XML Format Spreadsheet (XLSX) file, or into several detailed JSON files. JSON files have been exploited in the context of this work. The Figure 3.6 presents the content of a single file in Quartz database.

3.3.2.2 *Ontology generation*

Generation of CProduct ontology Using Apache Jena Foundation (2018) in a Java API, the GetNomenclature XML file was used in order to generate the Construction Product (CProduct) ontology with the prefix ***cproduct*** and the URI http://mindoc.enit.fr/voc/ConstructionProduct. From each Nomenclature_Item in the GetNomenclature file, a concept with the same "Nomenclature_Item_Name", "Nomenclature_Item_ID" and "Parent_Item_ID" is created. Depending on the value of "Parent_Item_ID" characteristic of each item, "subClassOf" relationships are created between concepts. Based on INIES and Quartz documentation and the goal of CProduct ontology, some concepts and relations are added and all necessary annotations are added to the ontology. CProduct is then aligned to an existing ontology, named Product ontology Schema.org (2018). The latter is already aligned to the BOT, thus enabling the mapping with building data for the environmental assessment of the building.

The algorithm underlying CProduct's semi-automatic generation is displayed in Figure 3.7.

Generation of INIESOnto In order to generate INIESOnto, GetAllFDESFullDataById request was sent. This request allows the retrieval of all the data contained in each FDES or about a specific product by precising its id.

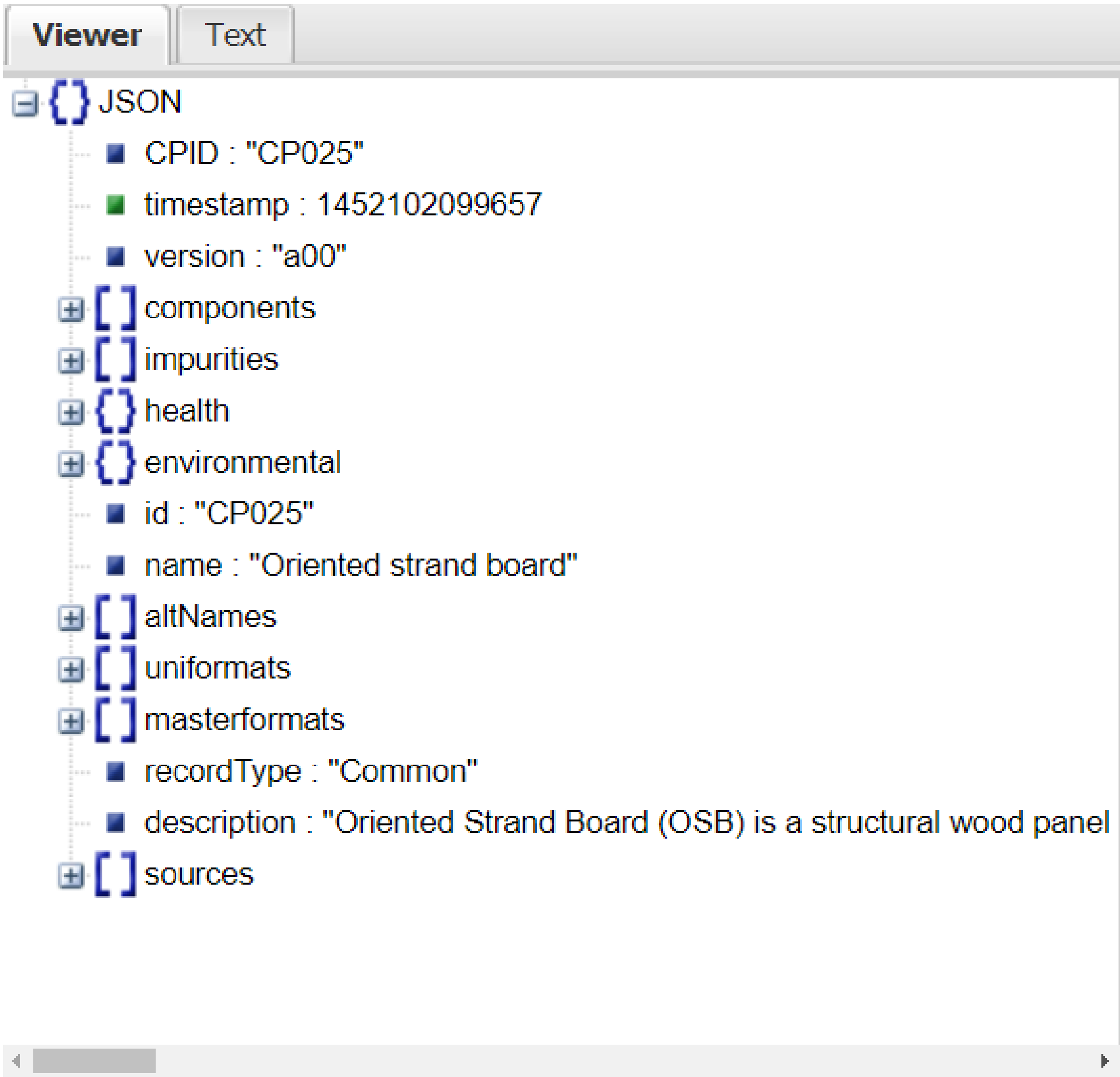

Figure 3.6: The JSON file of the construction product "Oriented strand board" in Quartz database.

Each construction product in Quartz has many characteristics such as id, a name, a list of components or impurities, an environmental object, a list of sources, etc. Squares(blue/red) represent charcteristics: CPID, version, description, etc. JSON objects are represented with curly braces and have characteristics: environmental and health. Finally JSON arrays are represented with brackets and can contain a list of JSON objects or a list of JSON arrays: components, sources, etc. This display has been produced using the online tool http://jsonviewer.stack.hu/

As a result of this request for any product, all available data on LCA of the product were obtained and stored in an XML file. This includes a list of constituant products, health data, a set of quantity gauges, etc. Using the latter XML file,

Algorithm 1 Semi-Automatic generation of ConstructionProduct ontology

Input

NX : getNomencalture.xml
ML : list of material categories
Gp : list of generic object and data properties of construction products

Output

$CProductontology$: the Construction Product ontology stored in ConstPOnto.ttl file

Variables :

nP : Namespace of schema.org ontology
$nsOWL$, $nsRDF$, $nsXSD$, $nsDC$, $nsVANN$, $nsRDFS$: Namespaces of common ontologies
pcP: Prefix of Contruction Product ontology
ncP : Namespace of Contruction Product ontology
bcP: Base URI of the Contruction Product ontology
lT: List of all meaningfull tags content in NX
T: any tag in NX
$TName$: name T
$TLabel$: data contained in T
$TiDLabel$: id of the item designated by T
PiU: URI of the parent of data contained T
iR: ontology resource attached to a statement
$modelRDF$: the RDF graph that holds the Construction Product ontology.

initialization

nP $\longleftarrow$ *https : //schema.org/*;
$ncP \longleftarrow$ *http : //mindoc.enit.fr/voc/ConstructionProduct#*;
$bcP \longleftarrow$ *http : //mindoc.enit.fr/voc/ConstructionProduct*;
$pcP \longleftarrow$ "*CProduct*";
$lT \longleftarrow$Get("Nomenclature_Item_ID","Nomenclature_Item_Name", "Parent_Item_ID");
$iR \longleftarrow$ncP+pcP+"_"+TiDLabel;

```
Foreach T in lT do
IF T in NX THEN
IF TName = "Nomenclature_Item_Name" THEN
IF ! TiDLabel = "746" THEN
addStatement (iR ,nsRDF + "type" , nsOWL + "Class" );
addStatementLiteral_Language (iR, nsRDFS + "label", TName, "fr", "string");
EndIF
ELSE IF TNAME = "Parent_Item_ID" & !Nomenclature_Item_IDLabel = "746" THEN
IF Parent_Item_IDLabel = "746" THEN
addStatement(iR, nsRDFS + "subClassOf", nP + "Product");
EndIF
ELSE
PiU ⟵ "CProduct" + "_" + Parent_Item_IDLabel;
addStatement(iR, nsRDFS + "subClassOf", ncP + PiU);
EndElse
EndIF
EndIF
End Foreach
AddMaterialCategories(ML);
AddAnnotations();
AddGenericProperties(Gp);
assignCProductItemToAMaterialCategory(modelRDF);
createTurtleFile(modelRDF);
```

Figure 3.7: CProduct semi-automatic generation algorithm

another ontology was then generated with our Java API. Depicted in Figure 3.8, the generated ontology is called INIESOnto as it contains all properties that can be found in each FDES file. Having the URI http://mindoc.enit.fr/voc/INIESOnto, INIESOnto has as preferred prefix: ***fdes***. Holding only data properties that are specific to INIES, INIESOnto is generated separately from CProduct ontology but imports it. That means INIESOnto contains all concepts and relations from CProduct ontology.

Generation of QuartzOnto In order to generate QuartzOnto, a JSON file is randomly chosen in the Quartz database and its content read. Each characteristic of the product that is directly available becomes a data property in the QuartzOnto. As depicted in the Figure 3.6, *CPID*, *timestamp*, *version*, *id*, *name*, *recordType* and *description* become data properties. In addition, each object of the JSON file provoke the creation of an OWL class. Thus, *Environmental* and *Health* classes are created in QuartzOnto. In addition, a data property is created for each characteristic of any JSON object. Furthermore, each JSON array entails the creation of both an OWL class and an object property called "List_NameOfTheJSONArray. For instance the class "Components" and the object property "List_Components" are created as entailed by the JSON array "components". Each entity (OWL class, object or data property) created in QuartzOnto is aligned where possible to the corresponding one in CProduct ontology. The Figure 3.9 and 3.10 present QuartzOnto entities. Having the URI http://mindoc.enit.fr/voc/QuartzOnto, QuartzOnto has as preferred prefix: ***quartz***.

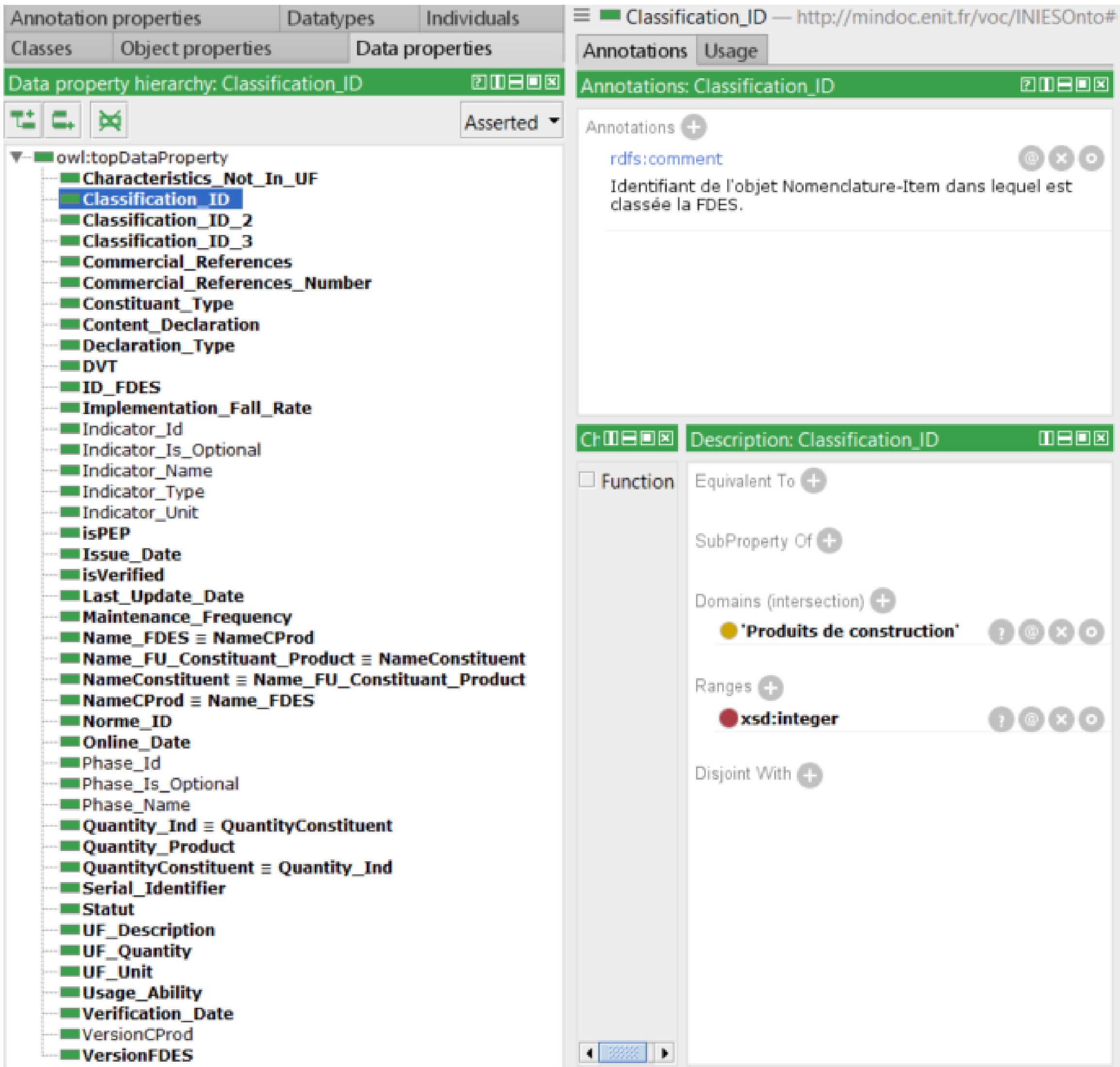

Figure 3.8: INIESOnto

3.3.2.3 *From data existing in databases to RDF graphs*

Obtaining data Using the CProduct and INIESOnto and QuartzOnto ontologies, a number of RDF graphs containing environmental data about multiple products were generated with our Java API, as described in Figure 3.11. Figures 3.12 and 3.13 present a part of the generated data.

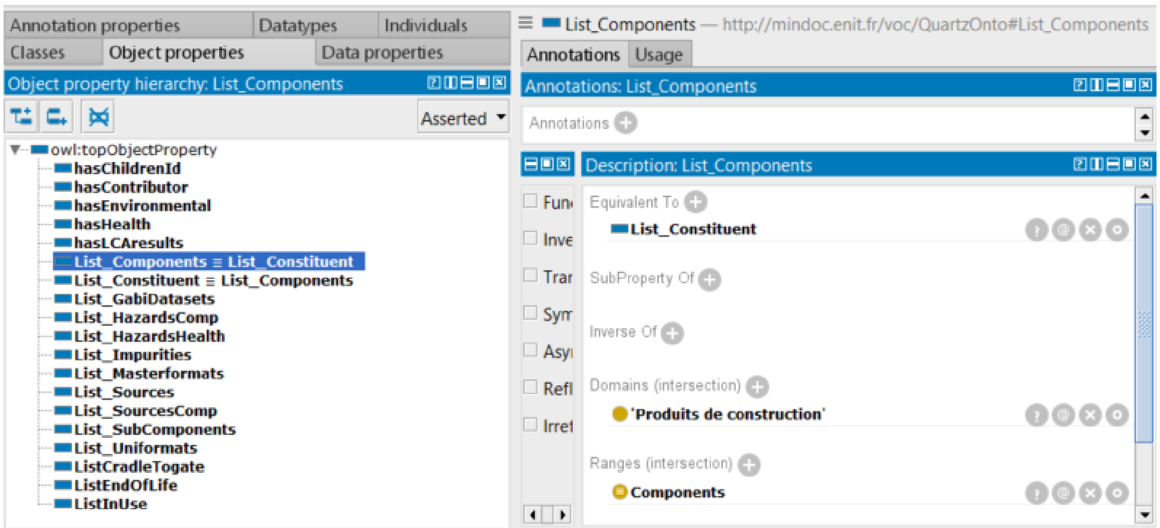

Figure 3.9: QuartzOnto - Object properties

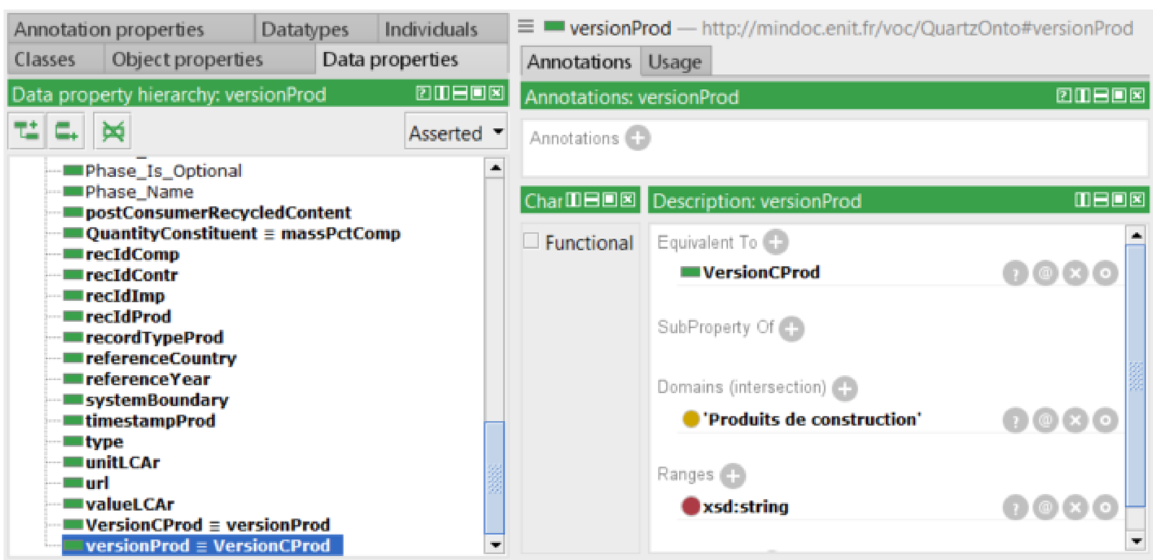

Figure 3.10: QuartzOnto - Data properties

Storage of data Once generated, environmental RDF graphs were stored into a Stardog triplestore. Developed in Java, Stardog is a knowledge graph platform that enables the storage of multiple triples with its Stardog server Union (2018). Using SPARQL, stored data can be queried and updated through desktop, web or command line user interface, as depicted in Figure 3.14. In addition, APIs like

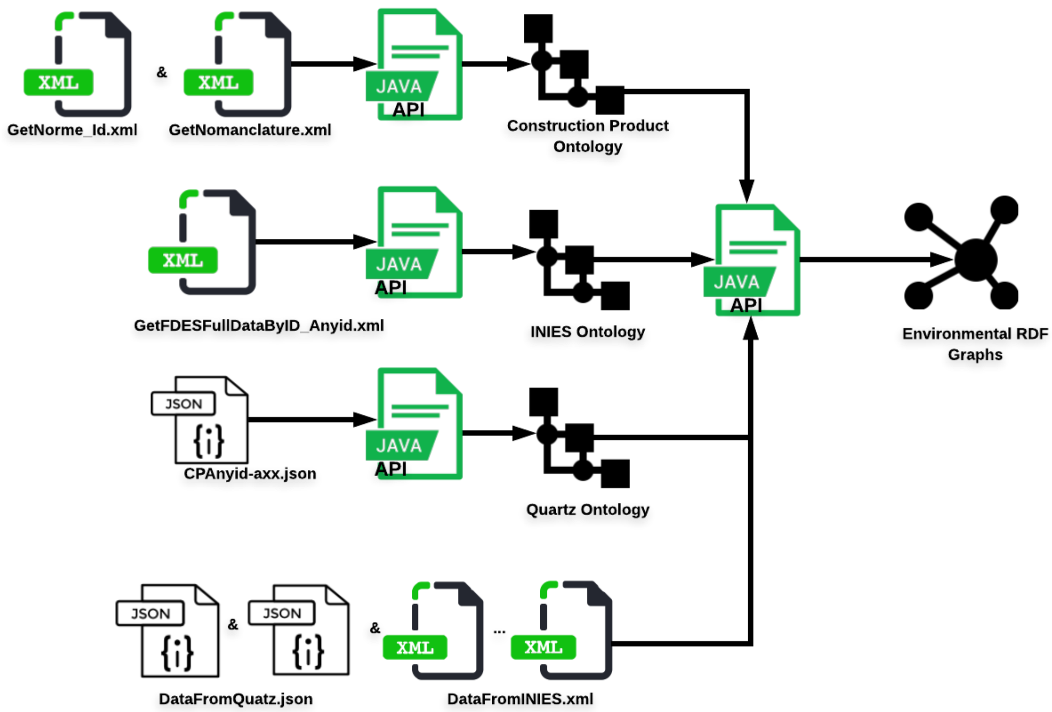

Figure 3.11: Generating Environmental RDF Graphs with ontologies & Java API

dotNetRDF library dotNetRDF Project (2018) have been used to interact directly with the Stardog server once it is launched. dotNetRDF is an open source .NET library to parse, manage, query and write RDF, but also to access RDF triplestores like Stardog or Jena through various user interfaces (UI).

An ontology for the categories of construction product has been generated: the CProduct ontology. Importing CProduct, the INIESOnto holds characteristics of each construction product as described in INIES database. Using those two ontologies with our plugin, any XML file resulting from IWS and containing environmental data about a particular construction product can be translated into RDF graphs and stored into a triplestore.

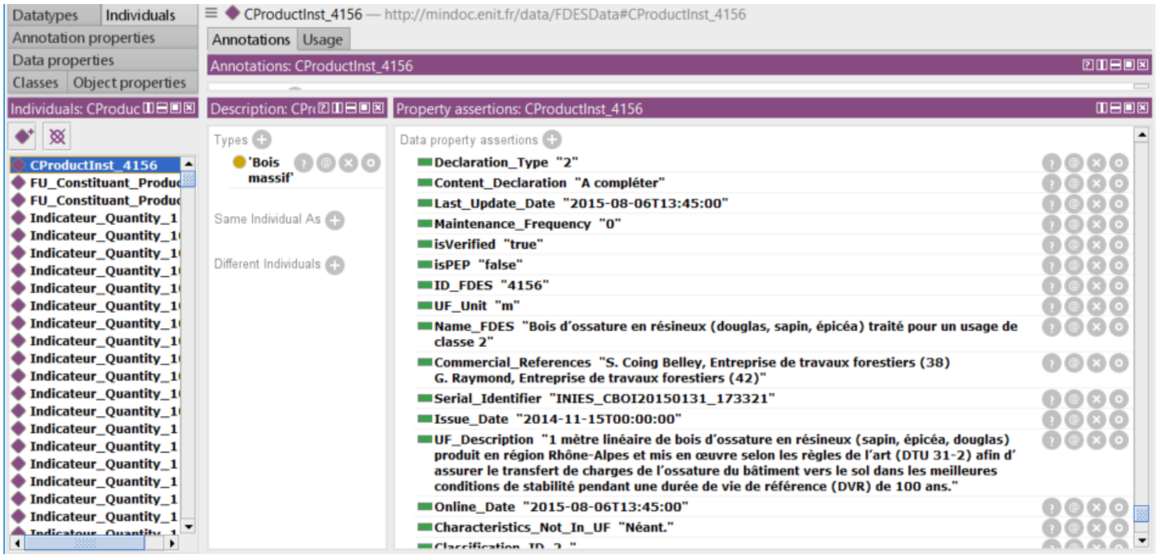

Figure 3.12: Translating INIES data into RDF Graphs with ontologies & Java API.

The URI used is http://mindoc.enit.fr/data/FDESData#CProductInst_4156

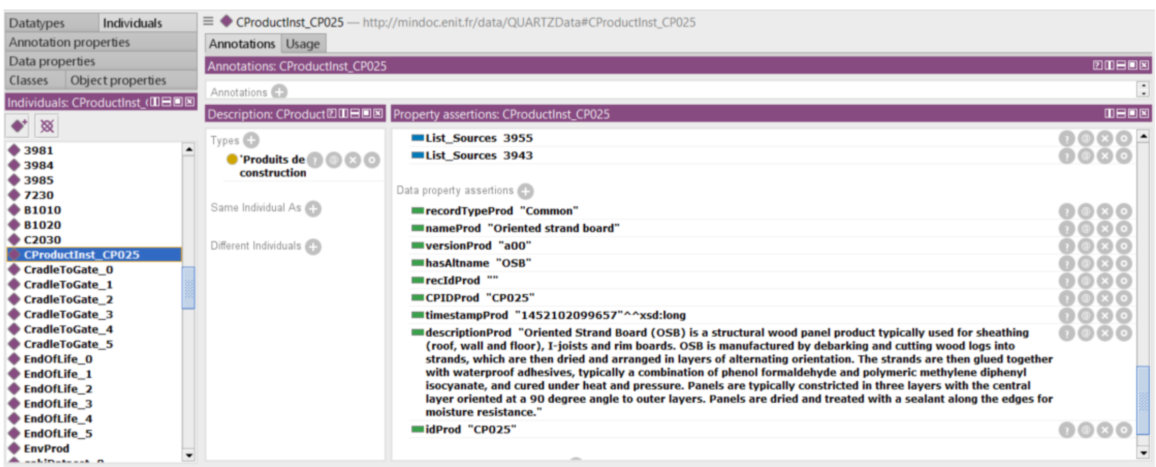

Figure 3.13: Translating Quartz data into RDF Graphs with ontologies & Java API.

The URI used is http://mindoc.enit.fr/data/QuartzData#CProductInst_CP025

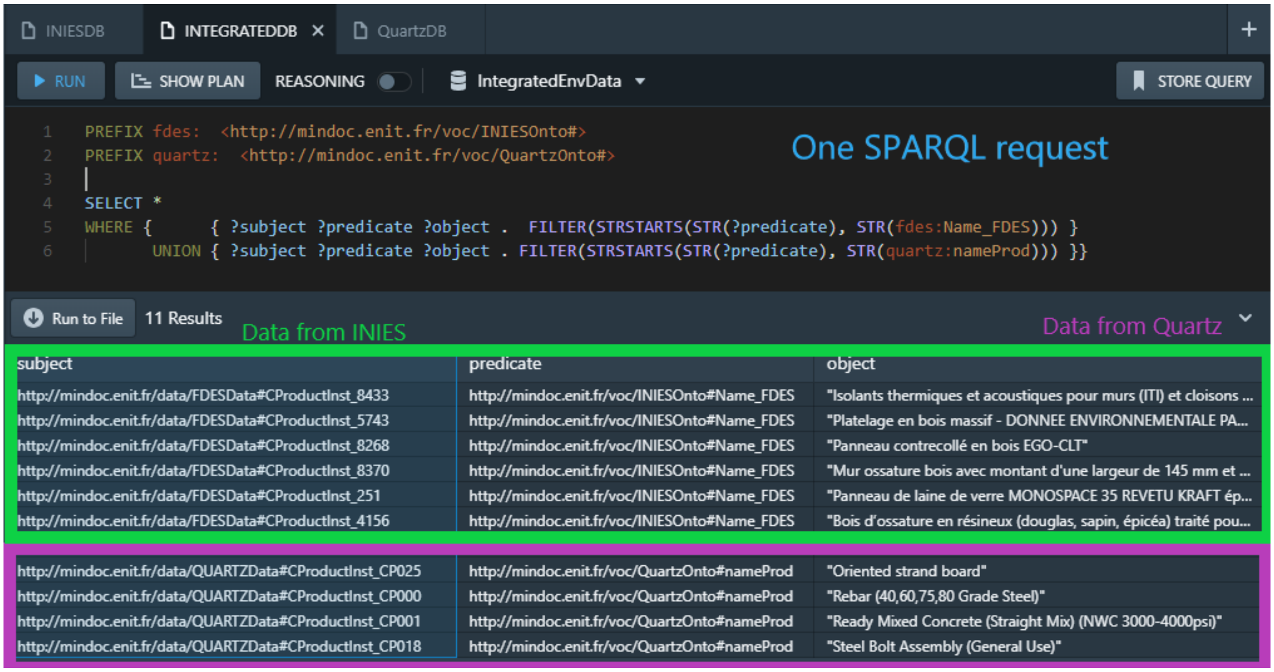

Figure 3.14: Environmental RDF graphs are store in a triplestore in Stardog Server and are queried with SPARQL

3.4 INTEGRATION OF ENVIRONMENTAL DATA IN BIM TOOL & LINKED BUILDING DATA

In order to properly do an environmental building assessment by taking advantage of our environmental RDF graphs in a flexible way, we need to give to the user an opportunity to choose products in a practical way and through its usual interface: its preferred BIM tool for example. The objective of the following paragraph is to present the implementation of our method to enable "Linked" EPD database access in a BIM tool and the generation of LBD embedded with environmental data.

3.4.1 Database access

Upon many existing BIM tools used in designing phase of BLC, Revit was chosen for our use case (Nagy et al., 2015; FinancesOnline, 2019). In fact, Rasmussen (2018) has developed a plugin to generate and export LBD from Revit. After adding URI and HOST parameters to each Revit project, the program generates a BOT-compliant Turtle file for the building itself, but also Turtle files respectively for properties, product classes and geometries. URI parameter is a URI assigned to each construction product on the Revit UI and HOST is the URI of the construction project on Revit.

In order to fulfil our need, we added the parameter named "ProductURI" to each object of the Revit project. The ProductURI parameter is the URI of a corresponding construction product in our triplestore of environmental data. This parameter is added by a brand new plugin which is an extension of the plugin developed by Rasmussen et al. The aim of this parameter is to store the URI of the product chosen by the user so that we can later query all LCA information about each product constituting the building. To enable the user to choose a product from the database, the list of existing products was uploaded in the UI. Behind the scene, the program queries the triplestore named "IntegratedEnvData", which contains all products with their environmental data and displays understandable labels of all available products in the UI in a combo box, as depicted in Figure 3.15.

3.4.2 User interaction

A Revit plugin has been developed as an extension of the one developed by Rasmussen et al. That plugin adds a tab called "MINDOC" to Revit UI. The UI of MINDOC tab is divided in three main features: the addition of parameters to the project (see left side of Figure 3.15), the product selection (see right side of Figure 3.15) and the generation of LBD. During the modelling, users should click on

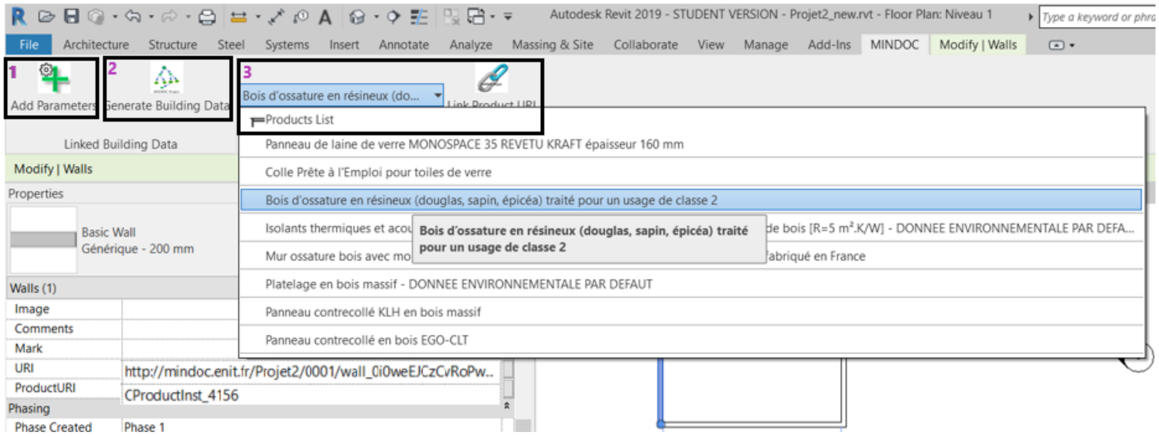

Figure 3.15: Product List in Revit UI

"Add Parameters" button in order to add URI and ProductURI to each element of the project and a HOST parameter to the project itself. Once added, they can assign to them corresponding values adapted to the project needs.

For the product selection, users select an element on the building, then select the product to which they want to associate it. Finally, they click on the button "Link Product URI" to assign the product URI to the ProductURI parameter of the selected element. Behind the scene, the program finds the URI of the selected product and assigns it the ProductURI parameter of the selected element. Figure 3.15(see the drop-down list at the right) shows how products from the triplestore are accessible from the UI.

When the modelling is complete, users click on "Generate Building Data" in order to generate the LBD of their building. As described in Figure 3.16, users have the choice to either to save data into several Turtle files or to dump data in the designated triplestore; then, the program generates the LBD. For the first choice, LBD is stored in several Turtle files. In the case data are dump to a triplestore (e.g Stardog), the triplestore is updated with the generated LBD, data can further be queried with SPARQL requests through a web page, the Stardog studio desktop application or the Windows command line UI.

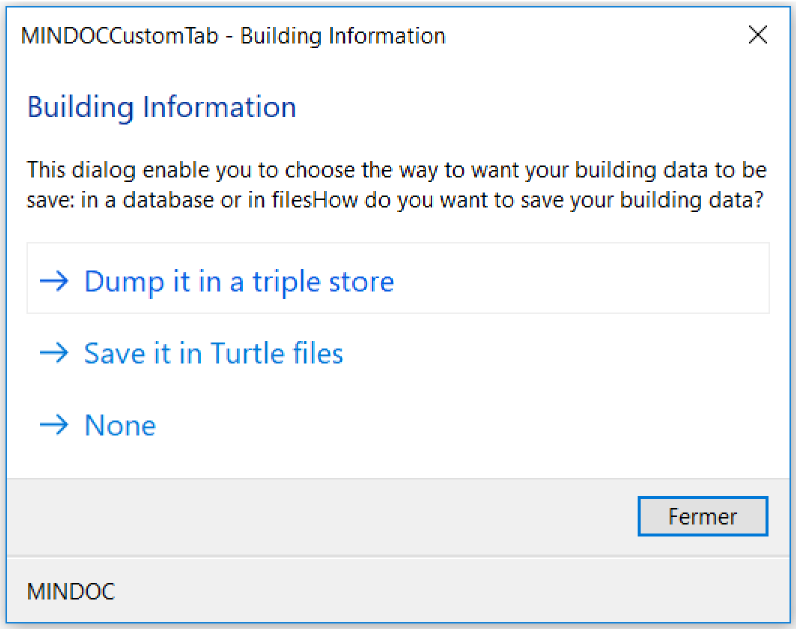

Figure 3.16: Generate LBD UI Dialog

CONCLUSION

The addition of classification criteria such as interoperability capacity or the percentage of eco-friendly has enabled us to provide a more affordable application layer for stakeholders. On the one hand, for the interest of databases in the flexibility of the exchange of information generated throughout the BLC and, on the other hand, for the use of environmental data on construction products to ensure the sustainability of the building to be built. In the context of this contribution, many ontologies have been semi-automatically generated: CProduct, INIESOnto and QuartzOnto. The implementation part of our methodology shows many results including classifying and integrating environmental data on construction products and then making them available to experts at early phases of the BLC.

Those results are proof that our methodology is another milestone experimenting with how deep the Semantic Web technologies can address issues in the core of the AEC industry. It is important to notice that information available upon the integration of INIES and Quartz database are static. That means, our methodology does not take into account any updates made by holders of the databases, since data are not uploaded online, but first store in a hard disk of a computer. A virtual integration of many EPDs databases which can take into account updates from each databases could be a reasonable follow-up of the work present in this chapter.

The ontologies generated contain definitions and descriptions that give meaning to the concepts and relationships addressed, therefor make them understandable by actors in play. However, we believe that they require a level of semantic disambiguation that could be provided by the use of a high level ontology.

CHAPTER 4

Enhancing semantic interoperability in BIM through ontology best practices

INTRODUCTION

One impediment to the uptake of BIM is the limited interoperability of different BIM systems. Several ontologies exist in the area of AEC industry. The CProduct ontology created in the previous Chapter adds essential knowledge about construction products for use in construction. At the meantime, BOT adds semantics to the generated LBD. However, we need more semantics in BIM data to ensure interoperability. The use of a BIM-based ontology is a serious approach that we are studying in this chapter.

Building on IFC, the ifcOWL ontology was developed in order to facilitate representation of building data in a consistent fashion across the Web by using the Web Ontology Language (OWL). However, ifcOWL has a number of weaknesses, turning above all on the fact that its terms lack definitions. This chapter presents a critical analysis of the ifcOWL ontology. We identify interoperability issues with ifcOWL and show how these issues can be resolved by using Basic Formal Ontology (ISO/IEC 21838-2) as top-level architecture. We here propose EifcOWL (for 'Enhanced ifcOWL') with the goal of improving codification of the data involved in building processes through an improved vocabulary in which such data are described in such a way that both machines and human will be better able to interpret the data received. In addition, we compare the original and enhanced ifcOWL ontologies on the basis of a set of competency questions. We then create an alignment of the enhanced ifcOWL with a second ontology - the ontology for building intelligent environments (DOGONT) - and demonstrate the added value deriving from

BFO by showing how querying the enhanced ifcOWL yields useful additional information.

The Section 4.1 highlights specific background related to the contribution of this chapter. Moving on, a critical appraisal of ifcOWL ontology is proposed (Section 4.2). Then, we introduce our methodology to enhance ifcOWL ontology (Section 4.3). Finally, an evaluation of our methodology is provided in Section 4.4.

4.1 BACKGROUND

4.1.1 Basic Formal Ontology

Basic Formal Ontology (BFO) is a top-level, and therefore very general, ontology developed to support information retrieval, analysis and integration in diverse domains (Arp et al., 2015). BFO has been widely accepted in a number of application domains and is currently in the final stages of review to become ISO standard ISO/IEC 21838-2. BFO consists of two main categories of entities: continuants and occurrents. Continuants are entities which continue to exist through time while maintaining their identity - for instance a building. Occurrents are entities that occur, happen, unfold or evolve through time. A BFO occurrent can be either an entity that unfolds itself in time, such as a process of construction, or the instantaneous boundary of such an entity, for example the beginning or ending of a process of construction.

BFO was developed initially to support integration of scientific data obtained through research. It has been used for this purpose in a growing number of ontology initiatives since 2005. BFO has a number of benefits, including:

1. serving as a domain-neutral, common starting point for ontology building

by those who work with specialist knowledge;

2. providing a common upper-level to support the interoperability of the multiple domain ontologies created with its terms;
3. promoting portability of expertise - a person who has been trained in its use in one area can easily apply the same method in other areas;
4. helping to ensure that ontologies built on its basis represent the universals in their respective domains in consistent and coherently structured fashion;
5. supporting the work of scientists and engineers at multiple scales and levels of aggregation;
6. supporting the integration of data relating to such multiple levels.

Currently 300 ontology initiatives are using BFO in order to exploit these benefits, including a number of collectively managed suites of ontologies organized in a hub-and-spokes structure in which BFO serves as hub. Examples in the engineering domain are provided in Industrial-Ontologies-Foundry (2019).

4.1.2 How to build an ontology?

The principal aim of any ontology is to support exchange of information on the basis of certain underlying semantic principles. To accomplish this, an ontology should have clear and easily accessible documentation. In addition, it is essential for each node of the ontology to be accompanied by a definition and by a list of synonyms. For an ontology to be of high quality, Arp et al. (2015) suggested 25 principles which should be adopted in its development. Table 4.1 captures some of these principles, together with those proposed by Smith (2006). Most of these principles are grounded in the fact that, since ontologies are built to be shared between actors from different domains, it is beneficial if the ontologies used in a given domain share an upper layer of well-defined terms that has been thoroughly tested in use. This upper layer should be domain neutral, since its aim is to represent the most general categories of entities and the most general relations within and between them, categories and relations shared by all ontologies at lower levels.

Table 4.1: Design principles for a good ontology.

N°	Principle	Description
1	Use singular nouns	To ensure consistent noun-verb agreement.
2	Use lowercase italic format for common nouns	To be in accordance with English language rules and for cross-ontology coordination
3	Avoid acronyms	To avoid oversights due to the short life and context-dependent use of acronyms
4	Associate each term in the ontology with a unique alphanumeric identifier	This identifier could uniquely locate a term in the hierarchy, for computer programming purposes or when a new version of the ontology is published, for example in a different language.

Continued on next page

Table 4.1 – continued from previous page

N°	Principle	Description
5	Ensure univocity of terms	For each term, the meaning should be invariant regardless of the context of use.
6	Ensure univocity of relational expressions	Each relational expression used should always have the same meaning
7	Avoid mass nouns	Mass nouns ('sugar', 'water') denote something that cannot be associated with a definite articular or with count. Use of mass nouns creates ambiguity as to whether we are talking about the item or the stuff of which it is made.
8	Distinguish the general from the particular	Terms in an ontology should represent what is general. Thus an ontology is a T-Box (for 'terminology'). It should be combined with an A-Box (for 'assertions'), when reference to individuals is needed.

Continued on next page

Table 4.1 – continued from previous page

N°	Principle	Description
9	Provide all non-root terms with definitions	Provide a definition for each term to ease understanding and to facilitate reuse beyond the specific context in which it was defined
10	Use Aristotelian definitions (also called definitions via genus and specific difference)	A definition of the term 'S' should take the form *S =def. a G that Ds* where 'G' is the immediate parent term of 'S' and 'D' is that which differentiates instances of S from instances of G which are not instances of S.
11	Use essential features in defining terms	Essential features of a thing define what the thing really is. They are the constant elements in its structure.
12	Start with the most general terms in your domain	Define the terms from the top down in the ontology hierarchy.
13	Avoid circularity in defining terms	Do not define a term by using the term itself or a near synonym.

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Table 4.1 – continued from previous page

N°	Principle	Description
14	To ensure the intelligibility of definitions, use simpler terms than the term you are defining	Definitions should facilitate understanding of the term defined and thereby promote exchange of ontologies across disciplines and domains.
15	Do not create terms for universals via logical combination	For example avoid disjunctive or negative terms for universals and classes.
16	Definitions should be unpackable	Definitions should be substitutable for their defined terms without a change in meaning or truth value.
17	Structure every ontology around a backbone is_a hierarchy	Each ontology should have an is_a hierarchy having the structure of a directed, rooted tree.
18	Ensure is_a completeness	Every term in the hierarchy must be joined to the root of the tree by a path constituted by successive edges in the graph. Ensure ontological agreement between terms and their parents.
19	Ensure asserted single inheritance	Each non-root term has exactly one parent in the hierarchy.

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Table 4.1 – continued from previous page

N°	Principle	Description
20	The principle of openness	The ontology should be freely available for use without constraints.

4.1.3 Contribution of the existing ifcOWL

In view of the main goal of IfcOWL, which is to enhance interoperability in BIM, it can be concluded that the efforts described in Section 2.2, although significant, are still insufficient to ensure interoperability in the building domain. Due to the popularity of ifcOWL and the broad use of IFC in BIM, it is logical to consider ifcOWL as the most appropriate ontology to build on for the future, given that IFC has the ability to cover the entire building life cycle. ifcOWL has also been improved significantly over time (Pauwels & Terkaj, 2016) and thus has good prospects for being reused in the future, for example through alignment with other ontologies, such as Cproduct ontology, via BOT (Rasmussen et al., 2017b; W3C-LBD-CG, 2019). It is thus imperative to appraise IFC critically in advance of further improvements.

4.2 A CRITICAL APPRAISAL OF IFCOWL

4.2.1 Criticisms of ifcOWL

Since the introduction of ifcOWL by Beetz et al. (2009), a number of criticisms and enhancements have been proposed (Pauwels et al., 2017a). First, ifcOWL does not comply with many of the principles presented in Table 4.1. Many classes in the IFC schema do indeed represent entities in the building domain, but almost all classes are under the root class "Thing". Too many intermediate classes are missing, and this prevents ifcOWL from fulfilling a critical function of an ontology: that of providing a definitive, exhaustive and easily navigable classification of entities in its domain. Furthermore, none of the nodes has a description or a definition. Providing natural language definitions for each term is essential if an ontology is to support coherent (re)use across multiple communities in such a way that the results will be able to support computational reasoning across data deriving from different domains and different sources. Moreover, although ifcOWL includes an is_a hierarchy, it includes no partonomy (thus no use of mereological relations such as part_of). Thus, no partonomy relationship exists, for example, between IfcBuildingStorey and IfcBuilding.

Such problems can indeed be to some degree rectified by drawing on the definitions provided in the BuildingSmart documentation (buildingSMART International Ltd., 2008), were we find for example:
IFC:IfcBuilding = def. construction work that has the provision of shelter for its occupants or contents as one of its main purposes and is normally designed to stand permanently in one place.

Furthermore, when a storey is specified in the IFC building model, then it is associated in every case with a building: it is part of that building by virtue of its spatial location. The order of spatial structural elements comprising a building project as conceived by IFC goes from high to low: IfcBuilding, IfcBuildingStorey, IfcSpace. Clearly, therefore, a part_of relation can easily be included in ifcOWL and should be included to advance ease of use of the ontology.

ifcOWL was not developed from scratch, but rather generated automatically from an IFC data file using the API EXPRESStoOWL tool (Pauwels, 2018). Our goal in this section, however, is not to discuss how ifcOWL was developed, but rather to evaluate its structure and the extent to which it fulfils the interoperability requirements of BIM.

- ifcOWL complies with principle 1 in Table 1, since it uses only singular nouns.
- ifcOWL includes as acronyms only those derived from the International System of Units (SI) and from IFC itself. Thus, it comes close to satisfying principles 2 and 3.
- No identifiers are provided for the terms in ifcOWL, thus it is not compliant with principle 4. Identifiers are however indispensable, for instance in tracking terms as their definitions and use evolves through successive versions of the ontology.
- ifcOWL is compliant with principles 5-8.
- Since ifcOWL has no definitions for any of its terms, it is not compliant with principle 9, and thus its compliance with principles 10-14 and 16 cannot be evaluated.
- No negative terms for universals or classes (principle 15) exist in ifcOWL.
- ifcOWL is not structured around a single backbone is_a hierarchy. For although all terms are joined to the root of the tree by a path constituted by successive edges in the graph, the root is not a genuine ontology node but simply the Thing that is hardwired into OWL. Some terms, such as "BINARY", "IfcApplication", "IfcGridAxis" are then isolated from the rest of the hierarchy, since they are linked only via OWL: Thing.
- ifcOWL is not compliant with principle 19 as it embodies cases of multiple inheritances. For example, the class IfcProduct has two parents: IfcProductS-

elect and IfcObject; IfcProcess has the two parents: IfcObject and IfcProcess-Select; and so forth.

- The principle of openness (20) is respected since the ifcOWL ontology is available to all potential users (licensed by CC 3.0).

4.2.2 Restructuring ifcOWL

ifcOWL fulfils at best only some of the requirements of syntactic interoperability. In what follows we aim not to rebuild ifcOWL from scratch, but rather simply to improve it by adding definitions and by restructuring on the basis of the top-level ontology BFO. The choice of BFO as top-level ontology will help to enhance interoperability with Cproduct ontology or already existing ontologies in neighbouring domains such as the Relation Ontology (Foundry, 2019) and the Environment Ontology (EnvO) (Buttigieg et al., 2013), as well as with the ontologies being developed within the framework of the Industrial Ontologies Foundry (Wallace et al., 2018). At the same time, it should be noted that BFO is not the only candidate ontology that can serve this purpose. The Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE) (Gangemi et al., 2002), for example, has established itself as a useful top-level ontology in a number of relevant domains, such as hydrology (Hahmann & Brodaric, 2012). But where BFO has been re-used in a sustainable fashion in many ontology initiatives following a common set of best practice principles, reuse of DOLCE has been more haphazard, in part because DOLCE has not provided to its users the sorts of services provided by BFO (Barry, 2019).

4.3 ENHANCED IFCOWL (EIFCOWL)

4.3.1 Enhancing the ifcOWL ontology

Figure 4.1 shows the methodology we used in developing the enhanced ifcOWL ontology.

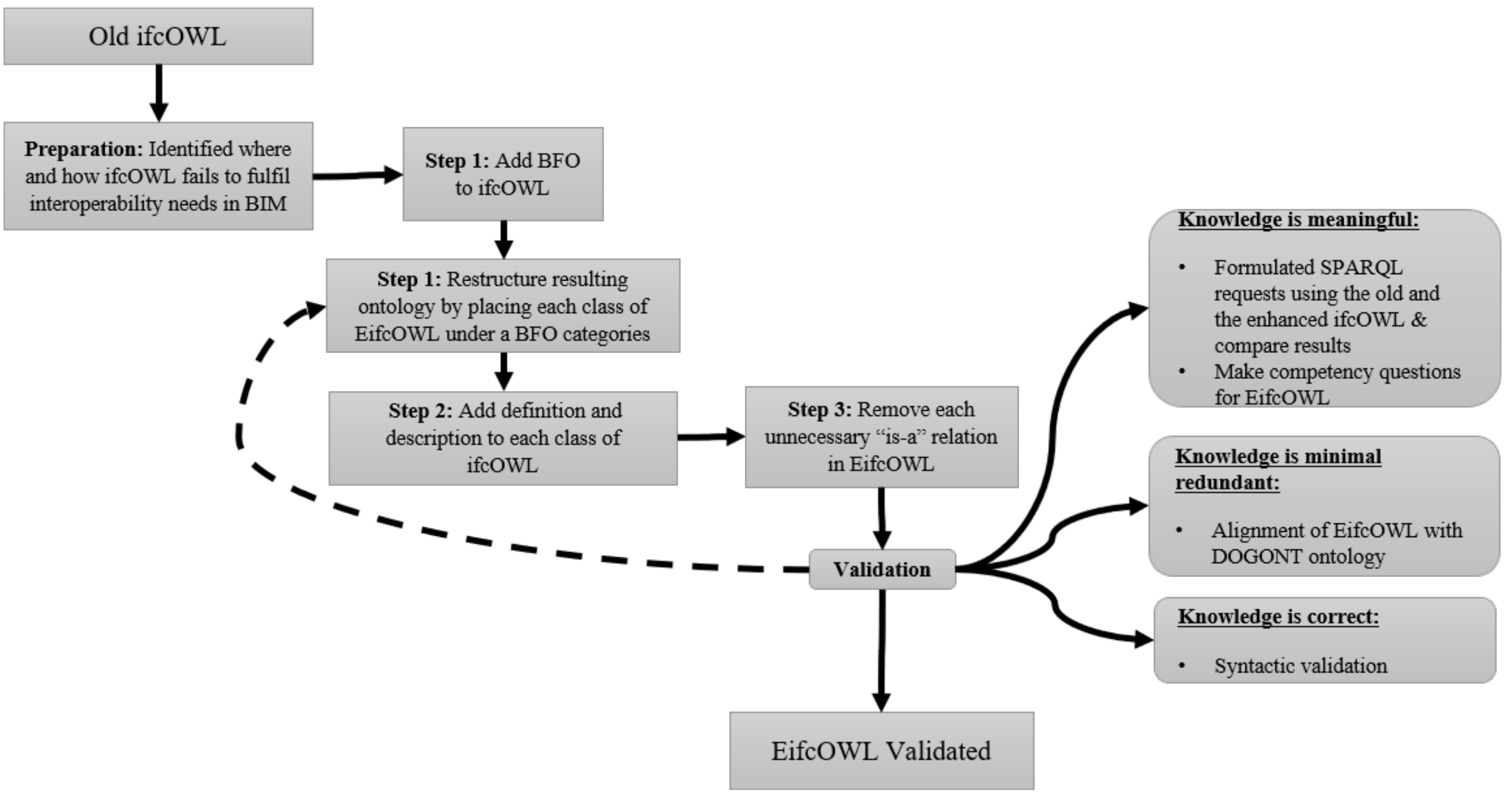

Figure 4.1: ifcOWL enhancement methodology

Restructuring of ifcOWL using BFO was conducted on the basis of prior work done in de Farias et al. (2016), Arp et al. (2015), Terkaj & Šojić (2015), Pauwels et al. (2017a), TERKAJ & PAUWELS (2017) and Pauwels & Roxin (2016). Use of BFO as top-level ontology provides a tested starting point for definitions and use of the Aristotelian form for the latter will at the same time allow validation of the terminological coherence of the enhanced ontology. Table 4.2 summarizes the key categories of BFO used in this enhancement.

Table 4.2: BFO Categories.

Category	Definition
Entity	Anything that exists
Continuant	Entity that continues or persists over time while maintaining its identity, and has no temporal parts. It is a dependent or independent object
Occurrent	Entity that occurs, happens, unfolds or develops in time: events or processes or happenings
Independent continuant	A continuant entity that is the bearer of qualities. It can maintain its identity and existence through gain and loss of parts or dispositions or roles, and through changes in their qualities
Generically dependent continuant	An entity that is dependent on one or more other independent continuants that can serve as its bearer. It is similar to complex continuant patterns of the sort created through the process of evolution.

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Table 4.2 – continued from previous page

Category	Definition
Specifically dependent continuant	An entity that depends on one or more specific independent continuants for its existence. It exhibits existential dependence and has two subcategories: quality and realizable entity
Process	Occurrent entity that exists in time by occurring or happening, has temporal parts, and always depends on at least one material entity. It can be partitioned into temporal parts in different ways and at different levels of granularity
Process boundary	The instantaneous temporal boundary of a process. It is the limiting or smallest temporal process part
Quality	An entity that depends or inheres in an entity at all and is fully exhibited or manifested or realized in that entity

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Table 4.2 – continued from previous page

Category	Definition
Material entity	An independent continuant that has some portions of matter as part is spatially extended in three dimensions and continues to exist through some intervals of time. It has three subcategories: object, fiat object part and object aggregate
Immaterial entity	An independent continuant that contains no material entities as part. It has three subcategories: site, spatial region and continuant flat boundary
Site	An immaterial entity in which objects are or can be contained. It can move through space and does not contain the retainer as part while it exists because of this retainer

4.3.1.1 *Step1: Addition of definitions on ifcOWL*

For the purpose of adding definitions to ifcOWL, we took as our starting point the definitions provided by buildingSmart for each term in IFC on the buildingSmart website (buildingSMART International Ltd., 2008). These definitions were then used to annotate the classes of the ifcOWL ontology in creating EifcOWL, using the Aristotelian form, which is the best practice for use in formulating definitions recommended in Arp et al. (2015):

S = def. a G that Ds

where *'G'* (for: genus) is the immediate parent term of *'S'* (for: species) in the ontology for which the definition is being created. *'D'* stands for differentia, which is to say *'D'* tells us what it is about certain *Gs* in virtue of which they are *Ss*. An example is provided in Figure 4.2.

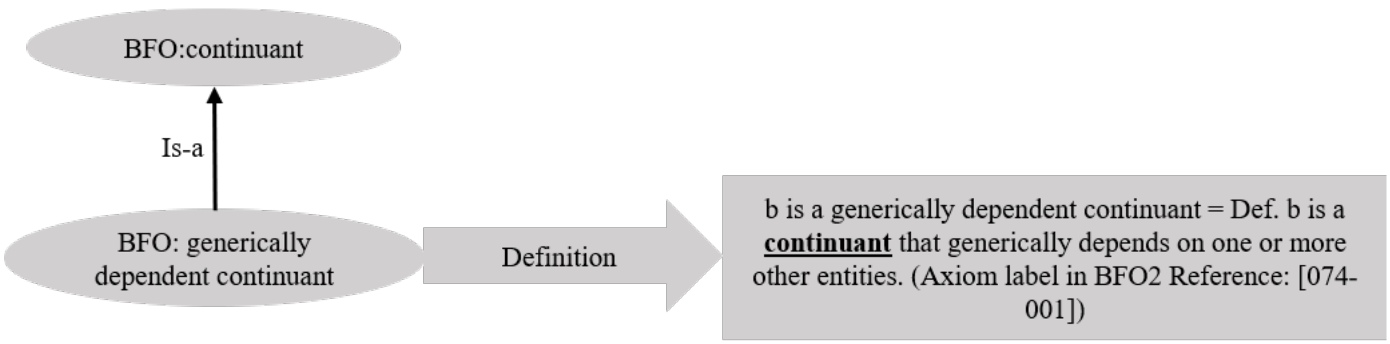

Figure 4.2: An example of an Aristotelian definition in the BFO ontology

In Figure 4.2, generically dependent continuant is defined with regard to its immediate BFO parent category of continuant, thus following the Aristotelian form. Examples of such definitions in EifcOWL are provided in Figure 4.3 for IfcProject and IfcProcedure, with parent terms IfcContext and IfcProcess, respectively. IfcProcedure is used to capture information about stepped processes such as calibration, start/stop procedures for equipment items, designated actions to take in the event of an emergency, and so forth. The main use of IfcProject in an exchange structure is to provide the root instance and the context for all other included information items.

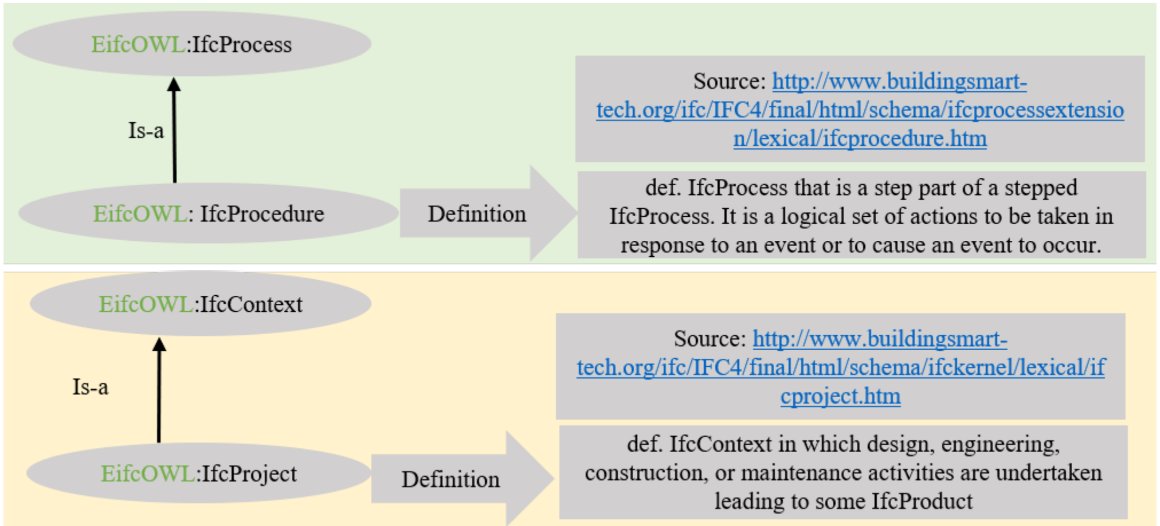

Figure 4.3: Examples of definition following the Aristotelian form in EifcOWL

To preserve the quintessence of the information found on the BuildingSmart website (buildingSMART International Ltd., 2008; Pauwels, 2014a) some definitions were imported without alteration even where they are not compliant with the Aristotelian form. This is so, for instance, in the case of the definition of IfcBuildingElement, whose parent is IfcElement (Figure 4.4), and of the definition of IfcProcess, whose parent is IfcObject. IfcProcess is defined as:
one individual activity or event that is ordered in time, which has sequence relationships with other processes, which transforms input into output, and may connect to other processes through input-output relationships. An IfcProcess can be an activity (or task), or an event.

These natural language definitions contain all the elements necessary for a good understanding of the IFC terms by human beings. The BuildingSmart documentation contains also definitions, descriptions and examples of usage for approximately 950 classes of the IFC standard. Examples of usage were added, as displayed in Figure 4.4, to clarify the meaning of terms in EifcOWL.

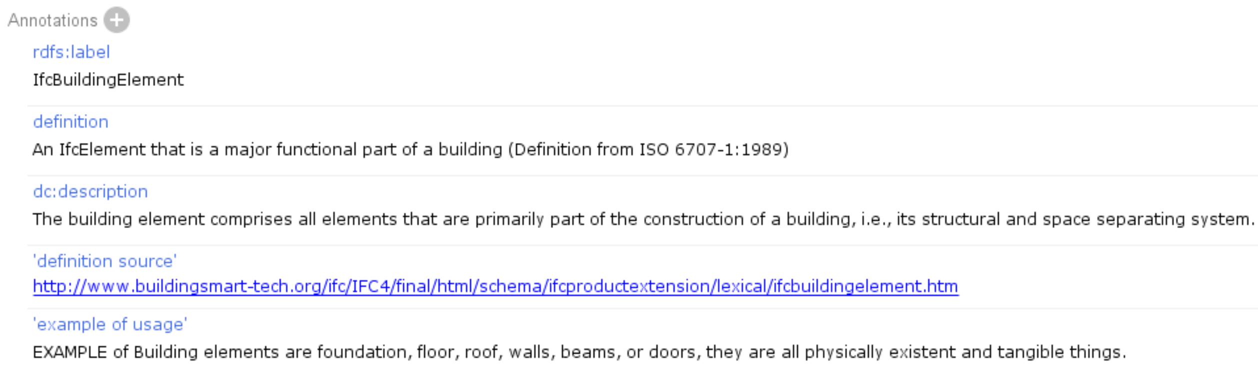

Figure 4.4: Some descriptions and examples of usage for each class

4.3.1.2 *Step 1 & 2: The restructuring process of ifcOWL using a top-level ontology*

The availability of definitions for all BFO categories is an important asset in this work. In order to link categories of BFO with EifcOWL concepts, we use the starting definitions for each term in its respective ontology. For example, to classify IfcBuilding under BFO object, we need to use the definitions:

1. BFO: object = def. material entity that is maximally causally unified (Arp et al., 2015; Gruber, 2009).

2. IFC: IfcBuilding = def. construction work that has the provision of shelter for its occupants or contents as one of its main purposes and it is normally designed to stand permanently in one place (buildingSMART International Ltd., 2008).

3. EifcOWL: IfcBuilding = def. object that has the provision of shelter for its occupants or contents as one of its main purposes and it is a construction work that is normally designed to stand permanently in one place.

The restructuring of EifcOWL then follows the flowchart presented in Figure 4.5.

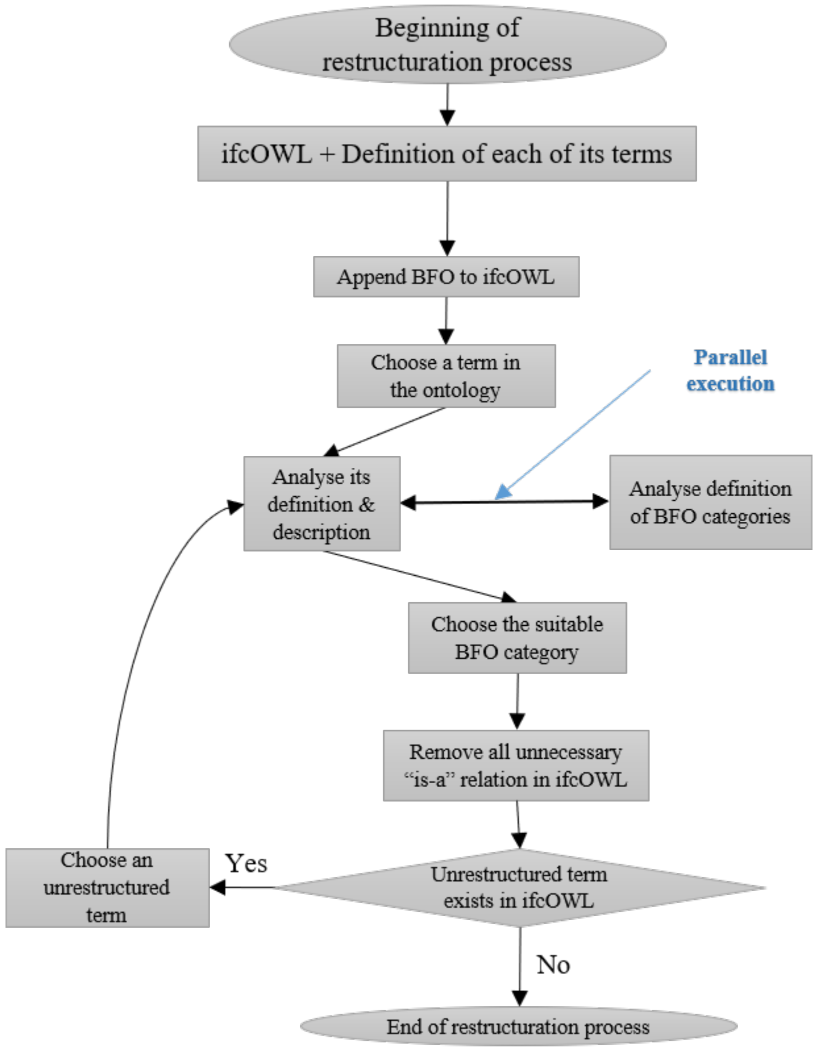

Figure 4.5: The restructuring process of ifcOWL.
The restructuration process starts after each term of ifcOWL has been associated with the appropriate definition. The latter is then analysed in relation to the BFO categories, a suitable BFO category is chosen, and all unnecessary "is-a" relations are removed from ifcOWL. The process is repeated until there is no more unrestructured term in ifcOWL.

The top-down aspect of this strategy involves using the BFO category definitions to work out for each ifcOWL class which category provides the most appropriate fit. The bottom-up aspect consists in reading and understanding the definitions of these classes in ifcOWL to confirm their suitability for the chosen category.

As examples of classes with non-trivial BFO-conformant definitions, consider IfcProperty and IfcPropertyDefinition, which are classified under BFO: quality and BFO: generically dependent continuant, respectively. Each IfcProperty instance has attributes such as: name, description, partofPSet, etc.

IfcProperty is defined in buildingSMART International Ltd. (2008) as follows:
IFC: *IfcProperty* =def. an abstract generalization for all types of properties that can be associated with IFC objects through the property set.
We define it in EifcOWL as follows:
EifcOWL: *IfcProperty* = A quality that is an abstract generalization for all types of properties that can be associated with IFC objects through the property set mechanism.

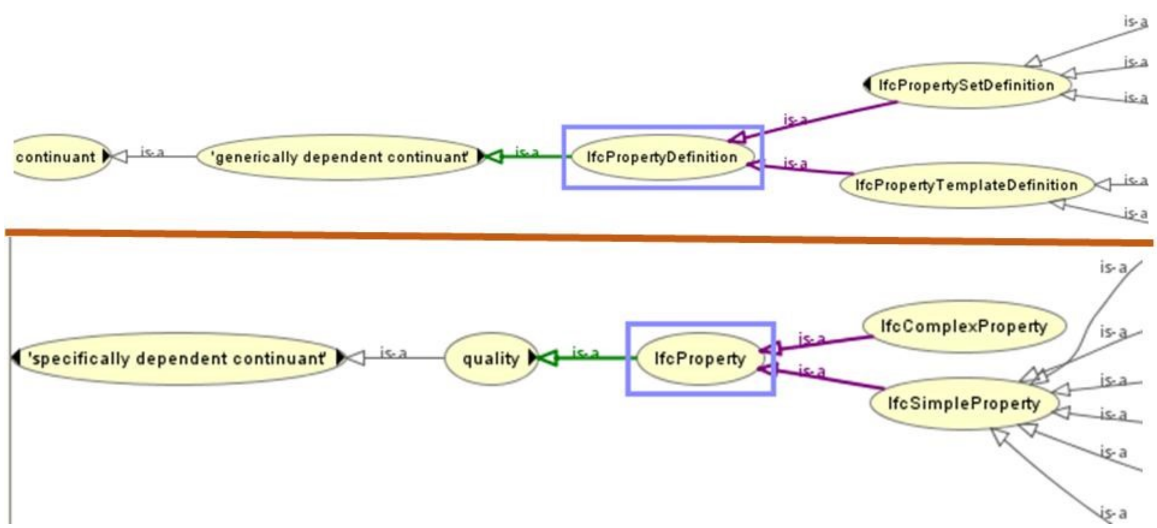

Figure 4.6: Categorization of 'IfcProperty' classes

In addition, information is provided in buildingSMART International Ltd. (2008) and allows us to understand, for each IfcProperty, the other entities on which it depends, or which are dependent on it, as depicted in Figure 4.6.

Current BFO:occurrent classes in EifcOWL include: IfcProcess, IfcTimeperiod, IfcTimeSeriesValue, and IfcDuration. The structure of these classes is presented in Figure 4.7. In fact, IfcTimePeriod is defined (in IFC) as a time period given by a start and end time.

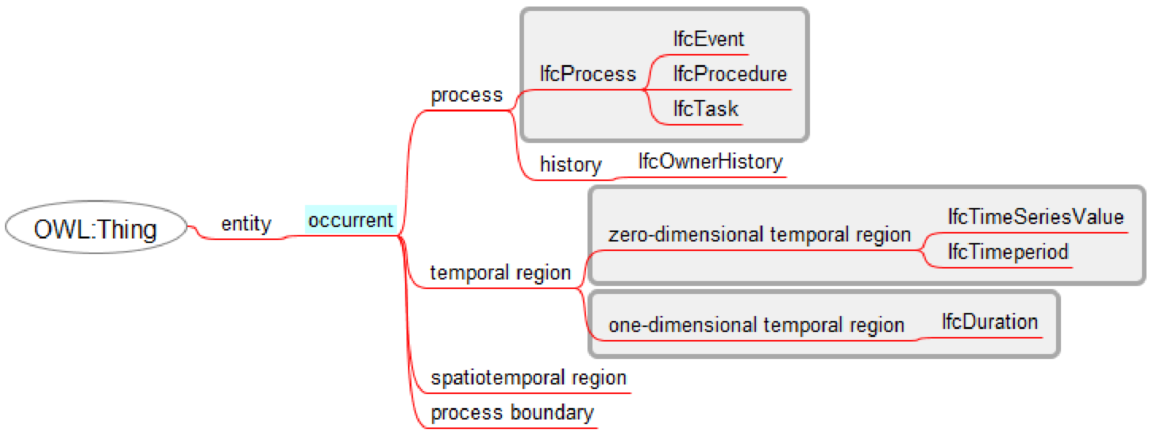

Figure 4.7: Examples of occurrent subcategories in the EifcOWL.
IfcEvent, IfcProcedure, IfcTask, IfcOwnerHistory, IfcTimeSeriesValue, IfcTimeperiod and IfcDuration were all classified as "occurrent" subcategories.

A synopsis of the structure of EifcOWL regarding BFO: continuant classes is presented in Figure 4.8.

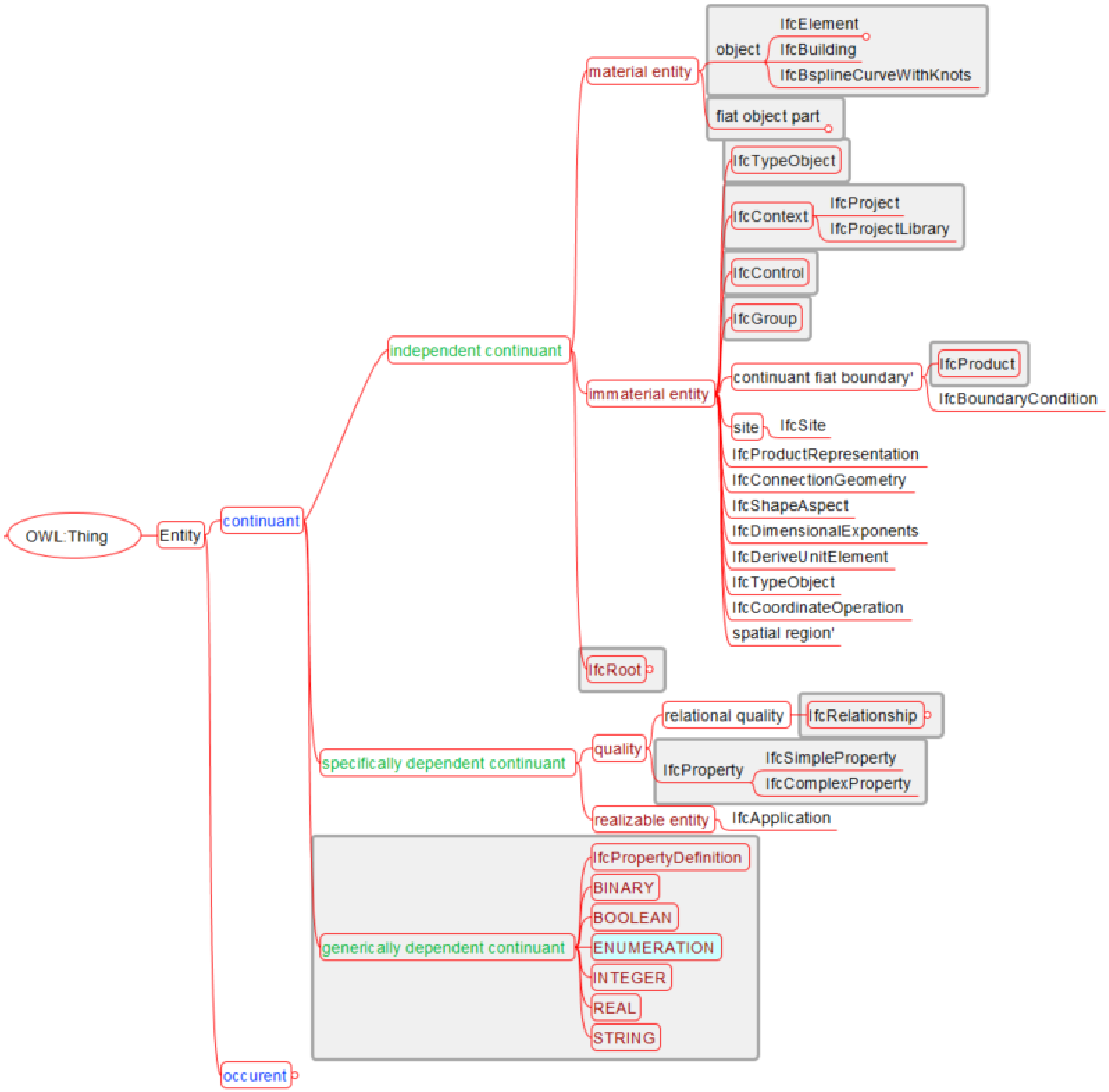

Figure 4.8: Continuant subcategories synopsis.
Many key terms in ifcOWL like IfcBuilding, IfcSite, IfcProduct or IfcRelationShip were classified as "continuant" subcategories.

At the end of the restructuring process, a persistent URL was created and the ontology was posted online[1].

[1] http://mindoc.enit.fr/voc/enhancedifcowl

4.3.2 Comparisons between ifcOWL and EifcOWL

In the course of this first phase of the restructuring, it was noticed that EifcOWL still does not comply with the single inheritance principle. To solve this problem defined classes were used. This provides a useful means of determining class membership. Examples of such defined classes in EifcOWL are: IfcProcess, IfcFillAreaStyleTiles, IfcProjectionElement, defined as follows:
IfcProjectionElement = def. a specialization of the general feature element to represent projections applied to building elements.

Differences between ifcOWL and EifcOWL are highlighted in Table 4.3.

Table 4.3: Comparison between old and enhanced ifcOWL

Metrics	Old ifcOWL	Enhanced ifcOWL	Including BFO
Class count	1294	1329	35
Class' definition Count	0	>555+34= 589	34
SubClassOf axioms	5035	5060	104
Axioms Added to	-	>100	1684
Axioms Deleted from	>50	-	
Axioms Total	20529	24911	1684

First, all classes (35) and axioms (104) from the BFO-OWL ontology have been included in the new ontology. However, some relationships are not used in EifcOWL, and the corresponding axioms are not included. On the other hand, some relations holding between EifcOWL classes and BFO categories have been added, with corresponding addition of new axioms. Starting out from zero in ifcOWL, EifcOWL contains more than 550 definitions.

Figure 4.8 and 4.9 highlight further differences between ifcOWL and EifcOWL. Figure 4.9 presents part of the structure of the *IfcRoot* class and its subclasses as they were structured in the original ifcOWL. Figure 4.7 and Figure 4.8 show how those classes were redistributed after the BFO alignment.

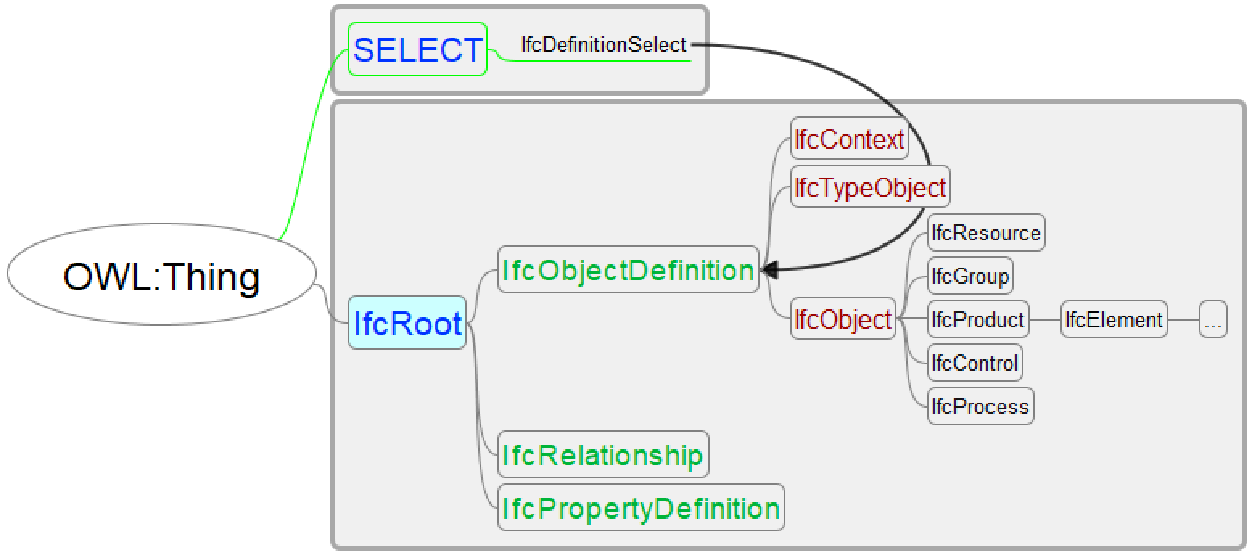

Figure 4.9: Old ifcOWL structure - IfcRoot and subclasses

Following the structure of ifcOWL as displayed in Figure 4.9, a relationship (resp. Ifcrelationship) is_a root (resp. IfcRoot) and a process (resp. IfcProcess) is_a objectDefinition (resp. IfcObjectDefinition), a group or a control (resp. IfcGroup or IfcControl) is_a objectDefinition, and so on. The later shows structural failings of ifcOWL because those axioms are semantically illogical.

For example, if we consider a building with two sorts of doors, for example interior doors or exterior doors, then it is important to distinguish them by specifying their respective functions: This information, which is available in most BIM software, cannot be modeled in the original ifcOWL ontology. Thanks to the additional high-level categories included in EifcOWL we can model information of this sort very easily.

4.4 EVALUATION OF THE ENHANCED IFCOWL ONTOLOGY

As proposed by Horrocks et al. (2003), a high-quality ontology should be: meaningful, correct, minimally redundant and richly axiomatized. The evaluation step aims to ensure that the enhanced ifcOWL meets as many of these characteristics as possible. To evaluate EifcOWL, three techniques used in ontology development have been used. First, the ontology was checked for its correctness and comprehensiveness. Second, the ontology was aligned with DOGONT, a well-established small ontology that we use to illustrate one use case for EifcOWL. Lastly, the enhanced ontology was queried to establish whether the results are conformant to our pre-ontological knowledge of the building domain.

4.4.1 ontology evaluation

The ontology evaluation or its logic validation consists in verifying the completeness and the correctness of the EifcOWL ontology. We were assisted in our task by the Hermit Reasoner in Protégé. For each inconsistency found, the "Inconsistent ontology explanation" window was used to tackle it. Moreover, the absence of red colour means that there were no more inconsistencies found in EifcOWL ontology.

4.4.2 Ontology alignment

In addition to the amount of information that can be leveraged from EifcOWL using the SPARQL language, the ontology is also useful if one wants to perform an alignment with other building-related ontologies. Ehrig (2006) defines ontology alignment as the act of finding for each term in the first ontology, the corresponding term in the second ontology. Ontology alignment will be partial if there is no corresponding second term.

This paragraph aims to demonstrate that alignment is facilitated by EifcOWL thanks to the addition of definitions and of BFO categories. DOGONT has considerable similarities with other building-related ontologies, including ifcOWL. For instance, the BuildingThing class in DOGONT corresponds to the IfcBuildingElement class. DOGONT is however very small, and it can thus be useful to AEC domain only if it can be complemented by other comparable ontologies. With regard to their names and available definitions, DOGONT classes were first binned under BFO categories to facilitate the alignment. EifcOWL is then aligned with the results obtained. The result of the alignment process is presented in Figure 4.10, where entities from DOGONT are in bold. The result shows that both "device", "controllable", "uncontrollable", "IfcBuilding" and "IfcPort" are children of "BFO: material entity". .

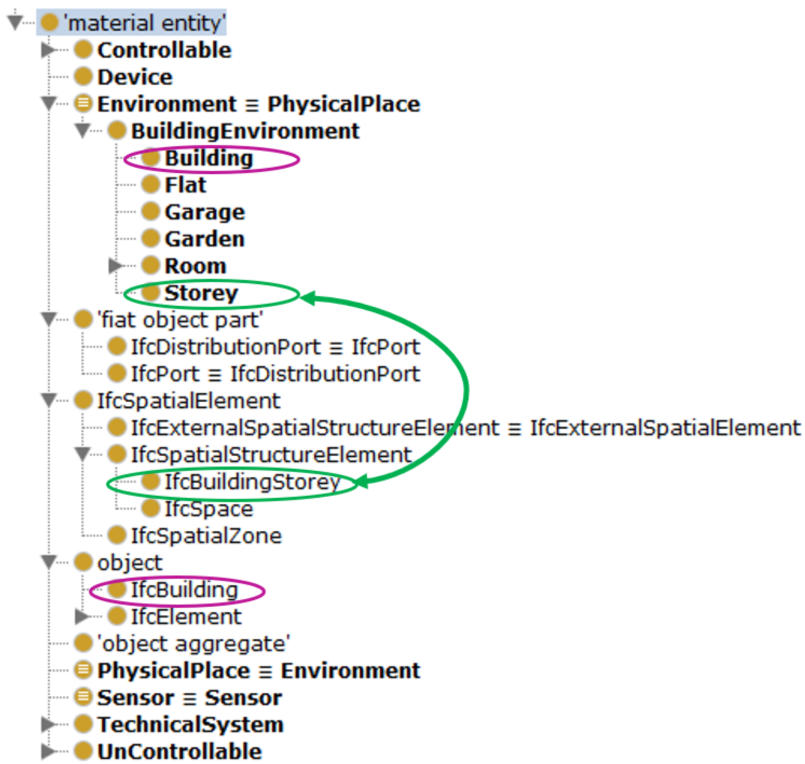

Figure 4.10: Alignment of ifcOWL with DOGONT when both are using BFO - material entities.

Qualities and functions from EifcOWL and DOGONT have also been aligned. Those correspondences can help experts to find useful information about a particular category of elements. As an example, some elements that can be controlled in a building such as ports (for example distribution ports for water or electricity) can be obtained through the alignment of EifcOWL and DOGONT ontologies as in Figure 4.10.

4.4.3 Querying the enhanced ifcOWL ontology

Since ifcOWL can make IFC data available in RDF graphs, SPARQL can be used for querying IFC data. However, there are no descriptions provided in the old version of ifcOWL, and so ifcOWL needs more annotations to enrich its semantics.

In EifcOWL, in contrast, there are many class descriptions, and an example of what results when EifcOWL is queried with a SPARQL request as shown in Figure 4.11. This figure presents both the request and the result. The later substantiates the result of the alignment.

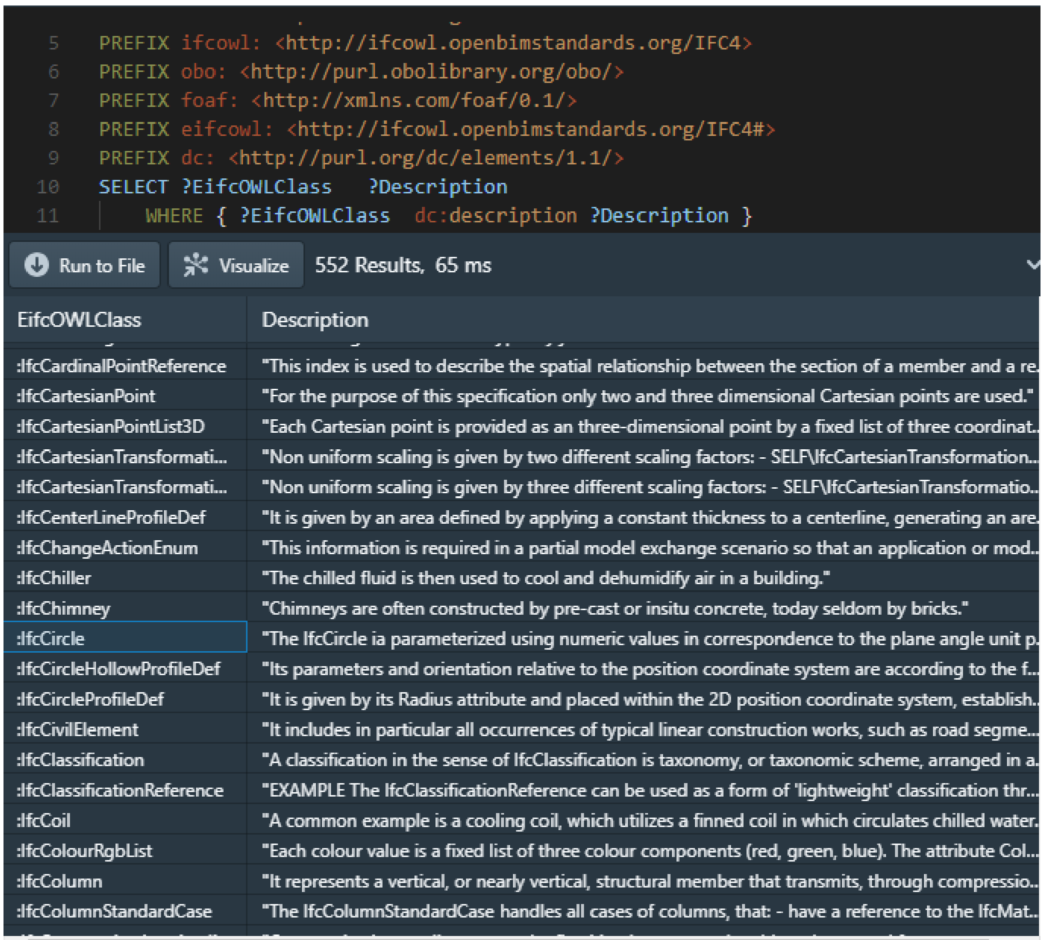

Figure 4.11: Requested descriptions in enhanced ifcOWL.
Descriptions are requested through a SPARQL request and are useful both for a human expert or for software.

Furthermore, the set of material entities (Figure 4.12) or the set of processes can also be extracted from the new ontology; demonstrating once again its great semantic richness.

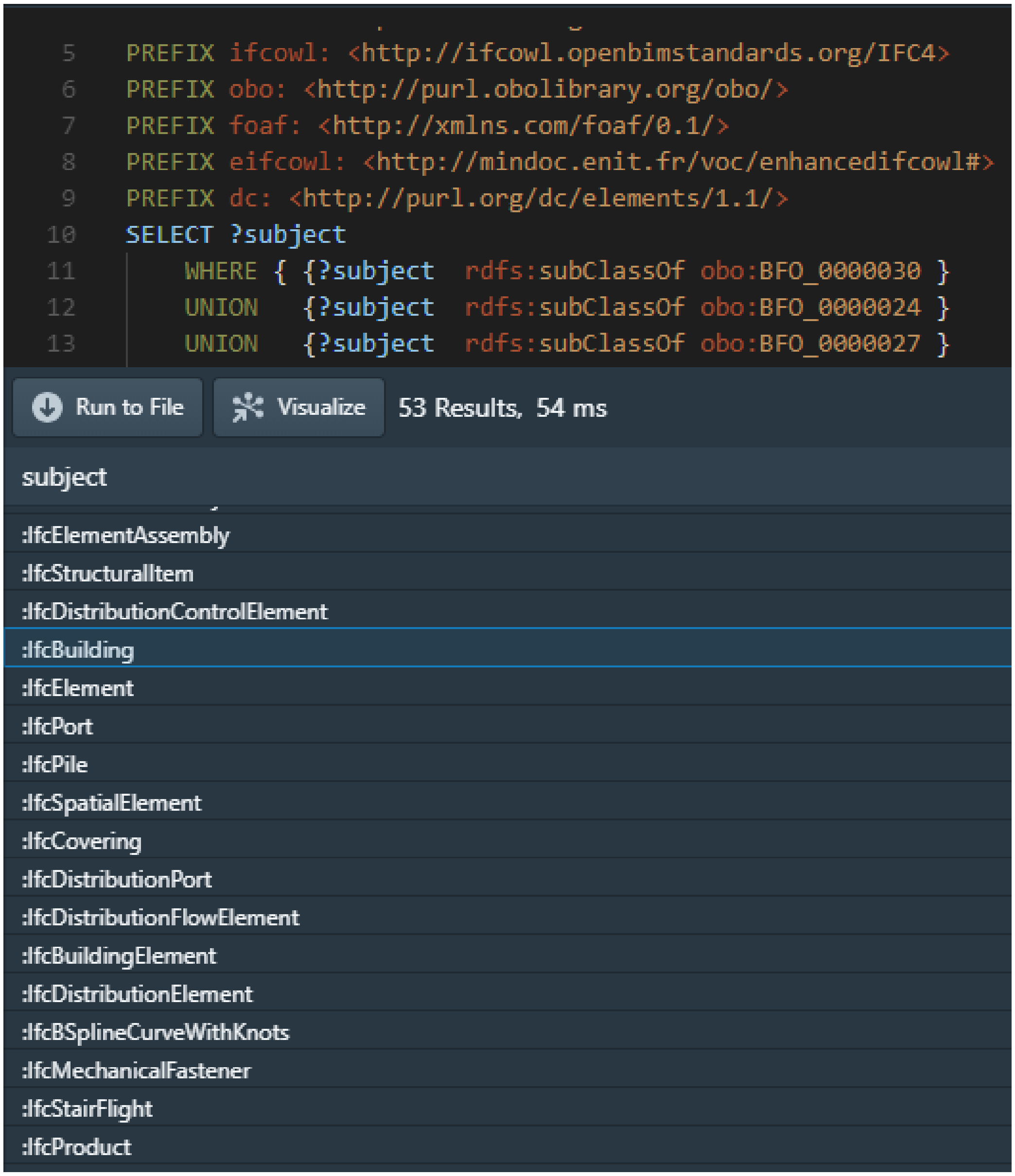

Figure 4.12: Some material entities requested from EifcOWL.
That means all EifcOWL classes that are classified under the BFO :material entity category at that time.

To show the level of enhancements of EifcOWL over IfcOWL, a comparison between the old and the enhanced ontologies has been conducted with the Protégé comparator API. The result (Table 4.4) clearly shows not only the addition of descriptions to each ifcOWL class, but also the addition of axioms, particularly those concerning subclasses. The enhancements bring much more details about the IfcBuilding as can be seen in Table 4.4, which highlight elements added, changed or renamed from the old to the new version: definition, descriptions, relations, and so on. We have noticed that in changing the superclass of terms in EifcOWL, there is a risk of non-compliance with previous versions of the ontology.

CONCLUSION

This study has served as the basis to explore and understand some issues in the ifcOWL ontology. We hope that the result of this work will foster interoperability between ontologies used in the construction especially in the BIM domain. During the life cycle of a building, the diversity of involved stakeholders attaches different meaning and different purposes to the same object as it evolves through time. We believe that the realism about such objects as they preserve their identity through time that is incorporated into BFO provides a solid basis for improved information exchange in the building domain - and this explains in turn our choice of a BFO-based top-level architecture.

Table 4.4: Ontology differences - examples related to IfcBuilding

Description	Baseline	New Axiom
Superclass changed	IfcBuilding SubclassOf IfcSpatialStructuralElement	IfcBuilding SubClassOf object
Added		IfcBuilding example of usage: "The IfcBuilding is used to build the spatial structure of a building (that serves as the primary project breakdown and is required to be hierarchical)."
Added		IfcBuilding definition: "Construction work that has the provision of shelter for its occupants or contents as one of its main purposes and is normally designed to stand permanently in one place. (Definition from ISO 6707-1:1989)"
Added		IfcBuilding definition source: http://www.buildingsmart-tech.org/ifc/IFC4/final/html/schema/ifcproductextension/lexical/ifcbuilding.htm
Added		IfcBuilding description: "A building represents a structure that provides shelter for its occupants or contents and stands in one place. The building is also used to provide a basic element within the spatial structure hierarchy for the components of a building project (together with site, storey, and space). A building is (if specified) associated to a site. A building may span over several connected or disconnected buildings. Therefore, building complex provides for a collection of buildings included in a site. A building can also be decomposed in (vertical) parts, where each part defines a building section.
Added		IfcBuilding label "IfcBuilding"

CHAPTER 5

Towards a MINDOC Sustainable Decision Support (MINDOC-SDS) tool

INTRODUCTION

This chapter presents the link between our previous contributions. It describes our use case and its instantiation with all created, enhanced or generated ontologies in the context of MINDOC project. Moving on, we compare the results with the State Of the Art. Then, we describe our proposal of what could be done in order to construct a MINDOC Sustainable Decision Support tool. Finally, we discuss on future works.

5.1 CASE STUDY

5.1.1 Description of the case study

Suppose we have the basic building called "BX" for "Building X", displayed in Figure 5.1. It has four walls, one window and one door.

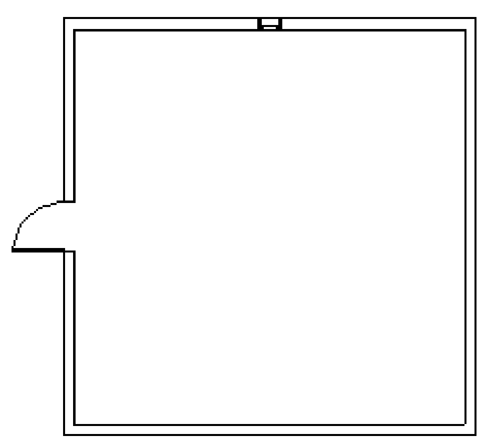

Figure 5.1: The Use case building: Building "X" (BX).
BX is a small building draw into Autodesk Revit Software

At Sketch phase, we have geometric dimensions of building elements and not enough details to perform the LCA of BX. The available information will evolve throughout the life cycle of BX. Our aim is to minimise the environmental impact of BX throughout its lifecycle. To achieve that goal, many obstacles are to be overcome. First, in early design phases, we need to query various EPD databases in order to perform the LCA of BX before the EXE stage, but their heterogeneity hinders our efforts. Then, We need to perform the EPA of BX but the variety of BIM-based formats are not going to facilitate the process because it causes loss of data. Moreover, BX needs to comply with a variety of standards and labels in force but the BX data are not sufficient to provide expected outcomes at early phases.

5.1.2 Description of our use case

A small-scale experiment was conducted to carry out an evaluation of our approach (Figure 5.1). During this one, we have manipulated a good dozen concepts that were instantiated in order to be further aligned to other building-based ontologies.

5.1.3 Comparison with the state of the art & Discussions

5.1.3.1 The contribution of CProduct ontology and other LCA-related ontologies

In the context of the case study described above, we have instantiated some of the building elements using through the user interface of the Autodesk Revit software. Result is displayed in Figure 3.15. Following the instantiation that assigns a construction product in the integrated database to each building element in the workspace, LBD of the sample is generated using the dialog displayed in Figure 3.16.

5.1.3.2 The EifcOWL contribution

Issues encountered when using ifcOWL ontology Suppose domotic experts would like to automate some operations in the building. Experts need to focus on elements that are concerned by the automating, i.e all material entities of the building. However, there is no possibilities neither for human, nor for programs to directly query all material entities of a building. With ifcOWL, the instantiation produces the following displayed in the Figure 5.2.

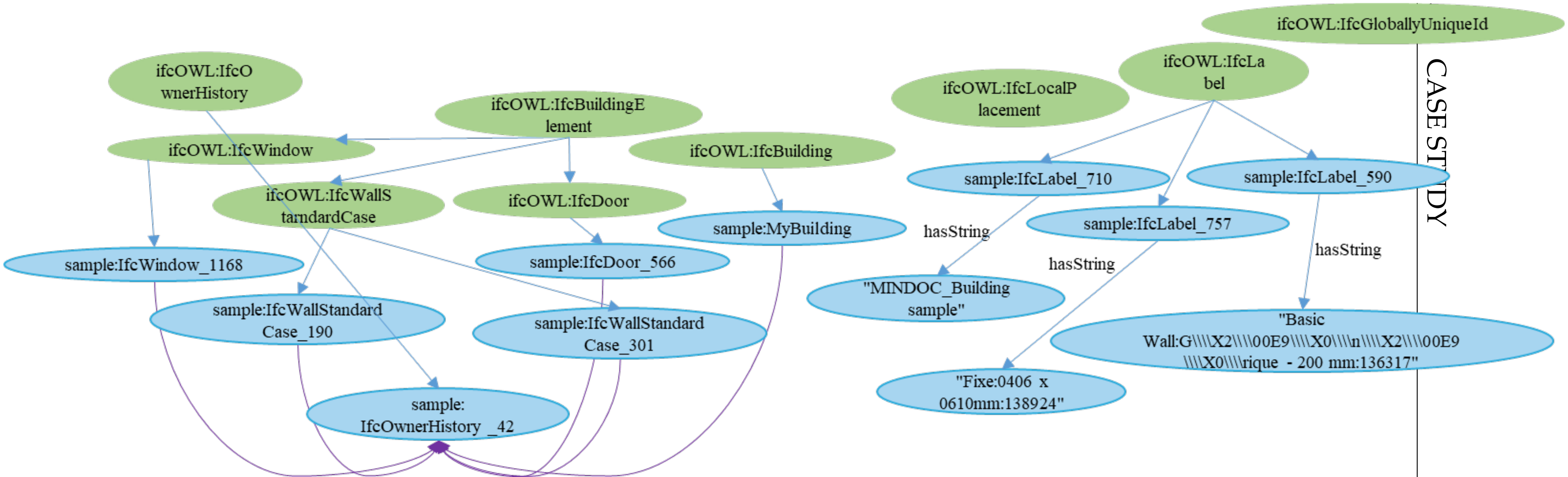

Figure 5.2: Instantiation of ifcOWL.

A sample building with 4 *standardcase* walls, one door and one fix window has been manually instantiated using ifcOWL ontology. The building called MINDOC_Building sample or "Building X" or "BX" shares the same owner history with all its buildingElement: IfcOwnerHistory_42

How EifcOWL improves the interoperability between experts EifcOWL allows a categorization of elements that was not available previously. That categorization is possible because of the availability of the definitions and descriptions of EifcOWL classes. Both for human and programs, the later improve the interoperability needed to achieve defined goals. The Figure 5.3 displays the instantiation of EifcOWL. A sample building with 4 standardcase walls, one door and one fix window has been manually instantiated using EifcOWL ontology. The building called MINDOC_Building sample shares the same owner history with all its buildingElement: IfcOwnerHistory_42.

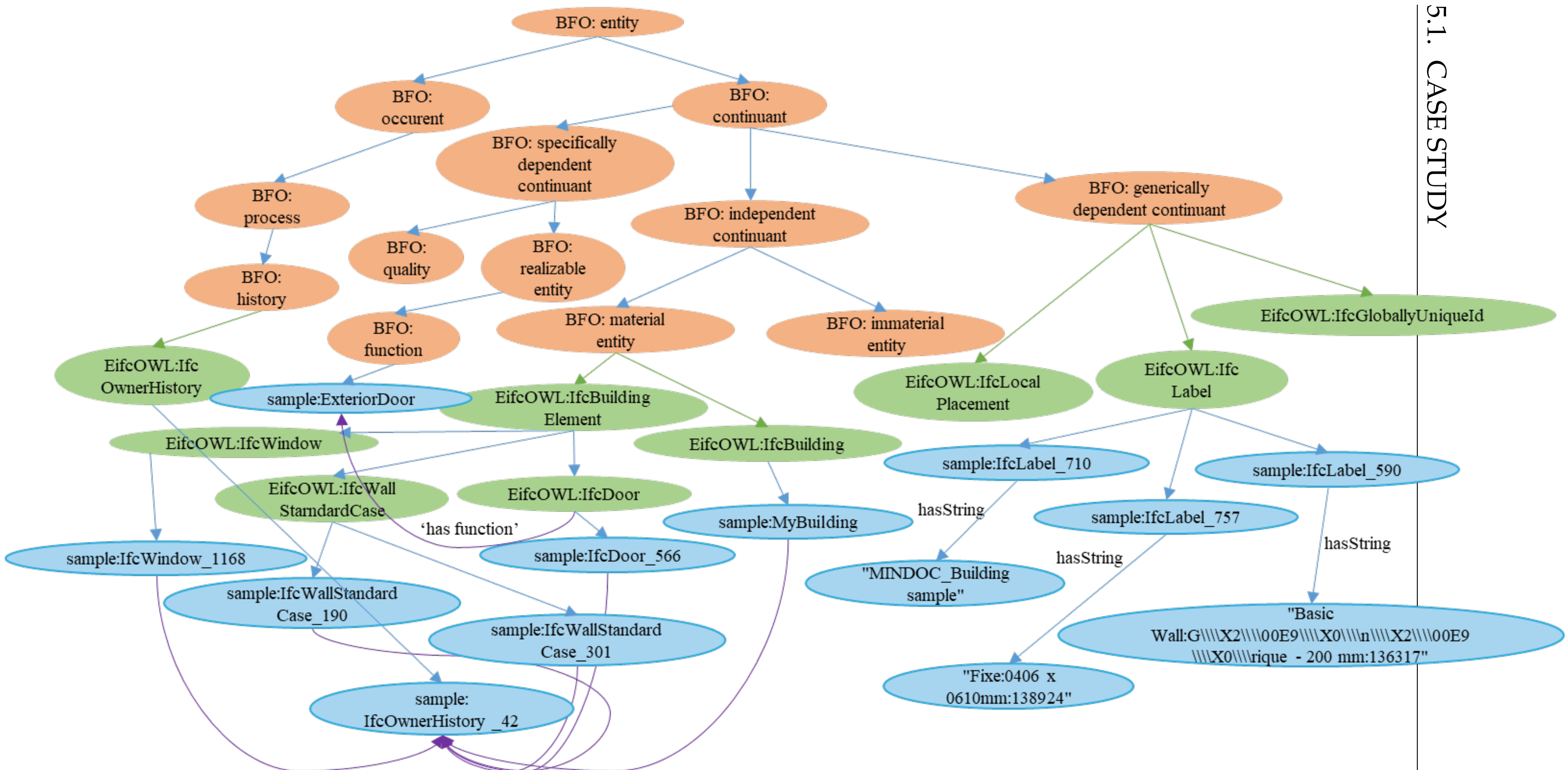

Figure 5.3: Instantiation of EifcOWL.

In ifcOWL, the information about some building elements like door or window are relatively poor and limited: only geometric characteristics, the globalId, the name, the objectPlacement, the objectType, the overallHeight, the overallWidth, labels, etc. are available. By taking advantage of the upper ontology BFO, function and disposition can be added to the model and thus enriched it. Know function or disposition of a particular helpful for instance to conduct the automating process of the building or to choose the appropriate material to associate to the element. For our sample building, we have added the function "Exterior-door" to a door. In a situation where we need to choose the appropriate material for that door, its specific function will be critical in that process.

5.2 TOWARDS A MINDOC-SDS

5.2.1 The method

In order to realize MINDOC-SDS tool, several preliminary steps are needed as described in Figure 1. The MINDOC-SDS methodology consists in the following stages:

1. Ontologies are semi-automatically generated using some environmental databases.
2. Construction products data are translated from their original format (XML or JSON) into RDF graphs and stored into a triple store.
3. The triple store that contains environmental data on construction products (Environmental RDF Store) is queried using SPARQL requests.
4. Construction products data are made accessible in a common BIM tool.

5. Experts assign construction product from the Environmental RDF store to each product on their workspace.

6. Linked Building Data that corresponds to the designed building are generated.

7. A constructive rule base is built to compare different alternatives of constructive solutions. It allows to verify that the products chosen by the expert comply with the constructive rules (or ideally to filter the products beforehand, in order to propose to the experts only those which, in a given constructive solution, comply with the constructive rules).

8. The assessment of a "Building X" (BX) is performed against the E+/C- label, using our SDS. In addition to our SDS, another label can be used or the environmental quality can be pursued without the need for a label.

9. The system outputs the degree of sustainability of the BX and a set of corresponding suggestions/improvements tracks. The latter must comply with constructive rules.

10. Results of the assessment are visualized in a BIM tool and elements to be enhanced are highlighted.

The methodology schema is presented in Figure 5.4.

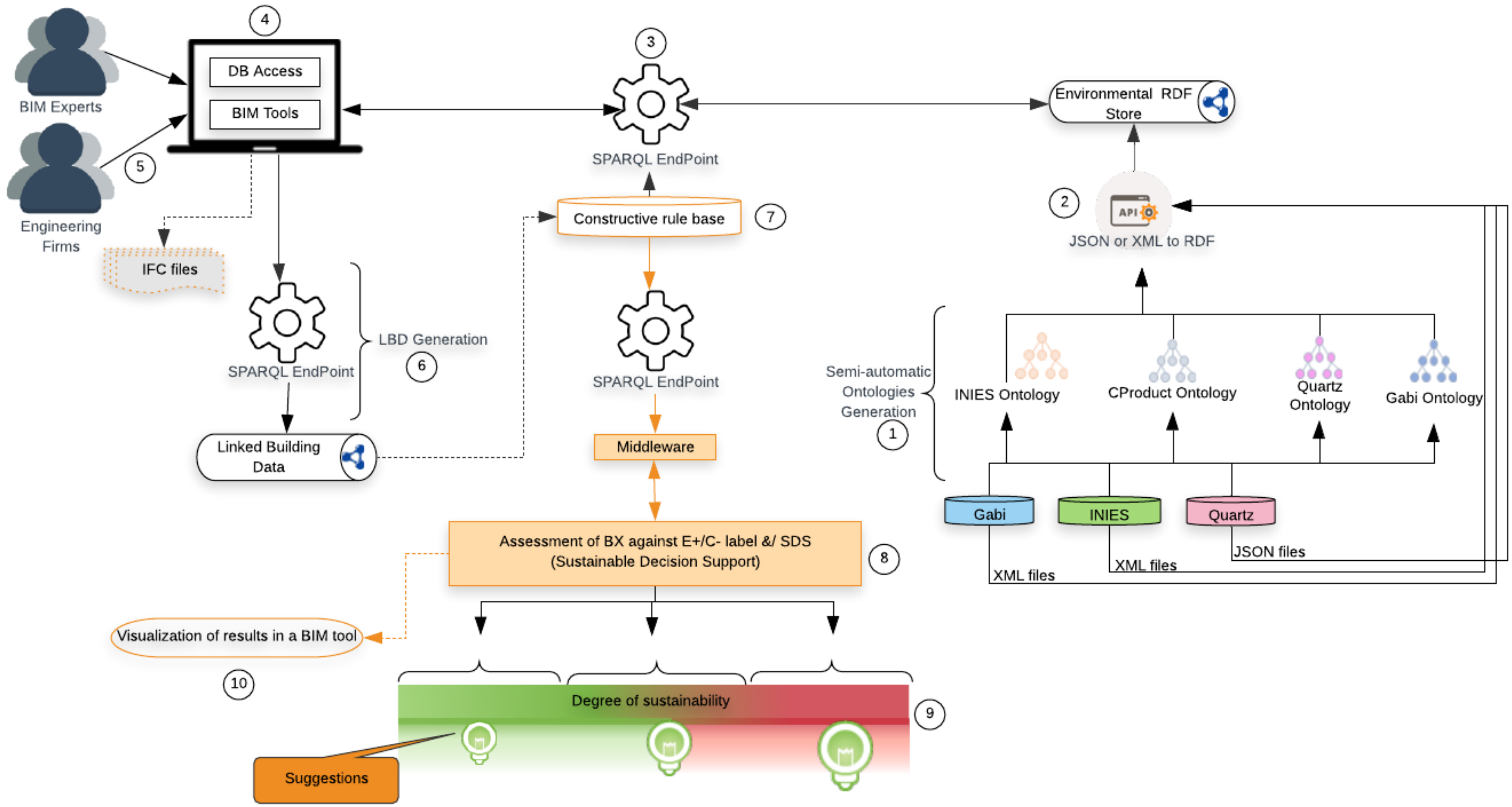

Figure 5.4: The MINDOC-SDS Methodology - 10 stages.

Inputs of the MINDOC-SDS Main inputs of the MINDOC-SDS are:First, there is the **EifcOWL ontology**: an enhanced version of the well known ifcOWL ontology. Secondly, we have **Integrated environmental data** that result from the integration of multiple EPD databases using semi-automatically generated ontologies. Then, there are **Linked Building Data**: The structuration of building data into RDF graphs stored into a triple store. Finally, we have a **constructive rule base**: A set of rules to ensure the reliability of constructive suggestions made to experts.

The assessment against environmental criteria Perform the environmental assessment using designated criteria comprises two core parts. Following the work of Xu et al. (2016), E+/C+ label rules could be expressed in the form of an ontology. Then, the MINDOC-SDS tool will be used to verify BX's compliance with a standard or label and as a decision support tool to improve the overall sustainability of the proposed solution.

Outputs of the MINDOC-SDS The MINDOC-SDS include two outputs:The level of sustainability of the building and suggestions to improve the sustainability of the building. Because there are multiple environmental impact indicators, the degree is not a value (or an interval) but rather a radar diagram.

Our thesis covers part of the proposed MINDOC-SDS framework: from stage 1 to 6. Remains stages will be covered in future works.

CONCLUSION

In this document we have proposed an approach using IT tools in design phases of the building project. In this case, we deployed artificial intelligence methods with a focus on the representation of knowledge with ontologies. To do this, we have implemented an approach that allows the integration of data with the consideration of their semantics. The objective is to provide the various stakeholders with the means to facilitate the environmental assessment of the building throughout its life cycle. The case study provides an illustration of the contribution of our approach, which offers users a software module integrated into their usual IT environment. In particular, for users of the Revit software, we have proposed a plugin allowing centralized access to data on construction products and their environmental properties. This provides an easy way to compare construction products from an environmental point of view in the future. As a result, it becomes possible for the user, for an expressed need, to compare solutions and select the most relevant one while keeping the alternatives according to the environmental criteria considered.

In the computer literature, there is several works focusing on data fusion and integration, particularly in multi-sensor, multi-source and multi-process frameworks. Frequently, it is the consideration of uncertainty that is emphasized in data fusion, particularly with the engagement of theories such as fuzzy logic or belief functions. However, it can be observed that there is little work that focuses on the use of formal means of knowledge representation to facilitate data fusion and integration. Our approach is to contribute to data integration using ontologies. Indeed, ontologies allow the formal representation of knowledge by specifying the concepts and relationships manipulated, but also the explicit reasoning on this knowledge. Thus, we have demonstrated that it is possible to combine Semantic Web technologies integrating ontologies to generate better data integration to address interoperability issues in the building industry. This is consistent with the future program for the definition of ontological language to encourage the integration of different levels of data sources using different system architectures such as edge, fog and cloud computing in the smart city domain as suggested by Lau et al. (2019), or latter in smallest domain such as building.

CHAPTER 6

General Conclusion

6.1 SUMMARY AND DISCUSSIONS

To enable an effective use of BIM throughout the BLC using Semantic Web technologies, the formalisation of both building data and construction product data is needed. In this work, we have introduce what is BIM, Semantic Web technologies and life cycle assessment of buildings (See Chapter 1). The main goal of our research is to enable an effective use of BIM throughout the life cycle of building in order to reduce the environmental impact building from its sketch to demolition or refurbishment. To achieve such a goal, we have introduced a combination of formalized building data and formalized construction data in a BIM environment, to enable a more flexible LCA process (See Chapter 3). Finally, we have enriched the semantics of building data by enhancing a well-known building ontology through the overexposure via the use of a high level ontology (See Chapter 4). This work provides answers to research questions raised in Chapter 2 by mean of the four main contributions that can be identified: (i) An approach for the integration of multiple EPD databases (ii) An approach for the inclusion of environmental data in building data; (iii) Enhancing semantic interoperability in BIM through ontology best practices applied to a well-know building-based ontology; (vi) Proposing a methodology towards a sustainable decision support called MINDOC-SDS (See Chapter 5).

6.2 CHALLENGES AND LIMITATIONS

In view of the state of the art, we conclude that there was a lack of Semantic Web approaches to perform the integration of BIM with LCA. In this work, we provide a way to integrate data about construction product at early stages of BLC by formalising both EPD data and BIM data and generating building data that contain references of environmental data. However, further developments are needed to fully address the identified gap. We acknowledge that the reduction of environmental impact of buildings consists also in better management of water, energy and waste during use phase. This work did not explore the possibilities of reducing the environmental impact of the building during the operational and end-of-life phases.

The state of the art on Semantic Web technologies in AEC industry reveals the lack of semantics in existing building-based ontologies. We have proposed an enhancement of ifcOWL ontology but the resulting EifcOWL needs to be aligned with newest building-based cross-domain ontologies like the Construction Product ontology. The latter will allow grasping another level of semantics in the practical use of Semantic Web technologies in AEC industry. Existing building-based ontologies that are aligned to the CProduct ontology are limited to the topology of the building while EifcOWL goes deeper in gathering even the processes involved in the BLC.

6.3 DIRECTIONS AND FUTURE RESEARCHES

Some of the identified future works comprise the implementation of a constructive rule base. The aim of the constructive rule base is to ensure the reliability of constructive suggestions made to experts. In order to implement the latter base, information could be collected from standardized labels, construction product experts, specialized forum, building construction experts and so on. Then, identified informal rules could be formalized using concepts in EifcOWL ontology. Moving on, rules could be written in SWRL language and checked. Finally, the resulting ontology could evaluate the knowledge base rule added to the MINDOC-SDS.

We may eventually consider to perform calculations on environmental data and perform the environmental assessment of the selected building. At the end of the MINDOC EPD integration framework, LBD generated from Revit software contain references of the corresponding environmental data for each construction product of the building. The latter references combined with LCA calculations rules could be used to perform the LCA of the selected building at each step of its lifecycle. After calculations, the system could output a degree of sustainability for each building and propose suggestions to experts for improvement. Operating in a multi-criteria environment, there will not be a construction product that will be better on all criteria. It is a decision to be made by the expert, a choice between impact indicators: why choose a product that has a very good carbon footprint, but requires significant water consumption? Would we prefer to use a product made from renewable materials but whose treatment will require the use of chemicals that emit pollutants in the air), etc.? Moreover, we could explore visualization of results of the decision support process on 3D model of the building in a BIM tool.

GLOSSARY OF TERMS

Building Information Modelling: BIM is a digital representation of physical and functional characteristics of a facility.

Interoperability: Interoperability is the ability of diverse systems, organizations and/or individuals to work together, using the parts or equipment of each other, to achieve a common goal, regardless of their divergences.

Life Cycle Assessment: methodological framework to assess environmental impacts associated with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling (defined in the DIN ISO 14040/44).

Ontology: a kind of representational artifact whose purpose is to capture what is general in reality by representing universals, defined classes and the relations between them using some combination of definitions, axioms, rules and constraints.

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