An integrated Linked Building Data system for improving environmental sustainability in AEC industry

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Abstract

Environmental assessment is a critical activity for ensuring buildings are performing according to specified requirements, and efficient, seamless exchange of building information is crucial for environmental assessment. Therefore, all those involved in built environment issues should be able to access and share not only building information but also data about products, especially environmental assessment results for the products used in building projects. Of the several approaches that have been proposed to achieve efficient information exchange, semantic web technologies are amongst the most promising due to their capability to share data and enhance interoperability between the most heterogeneous systems. This study proposes an approach that can be used to make environmental data available in the early phases of the building lifecycle. It relies on Semantic Web techniques, especially Linked Data principles, while building on emerging Building Information Modelling (BIM) technology to propose an approach that facilitates information exchange to enhance the sustainability assessment of buildings. The paper ends with an illustration of how lifecycle inventory databases can be integrated, linked to BIM software and used in exchanging environmental building data.

Keywords: Construction product databases, Linked Building Data (LBD), Environmental data, Building Information Modelling (BIM), semantic web, linked data.

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1. Introduction

To enhance the sustainability of buildings, participants in their construction and experts should be able to access and share data/information not only about the buildings but also about products that can be used in their environmental performance assessment. If seamlessly shared, such data or information can help experts make informed decisions about the environmental performance of buildings. Furthermore, the requirement for accuracy in environmental assessment computation makes it imperative to share information among all those involved. In recent years, in addition to their functional performance, the environmental quality of building products has become an important parameter for their selection and use in projects. A key element of environmental assessment is the environmental inventory database that contains the relevant coefficients for computing impacts of building projects on the environment. However, environmental databases are not homogeneous and are thus difficult to use when comparing results after computational assessment of performance. Some examples of heterogeneous data include differences in functional units, size, regional or international standards, and the methodology used for life cycle assessment (LCA). In addition, some of the environmental database inventories contain only a few construction products. Although several efforts have been made to resolve the challenge, Semantic Web technology remains one of the most promising solutions, with enhanced capabilities for sharing data and achieving interoperability between the most heterogeneous systems. It is against this background that this study aims to investigate the problem and propose a method that is useful for making environmental data available in early phases of the building lifecycle.

The rest of this study is divided into eight sections. Section 2 reviews the state-of-the-art on LCA for the building construction sector, the integration of multiple LCA databases, the integration of LCA data in a BIM environment and Linked Building Data (LBD). This is followed by a short overview of the research method in Section 3, and critical appraisal of the lifecycle inventory database (LCID) in section 4, where criteria useful for appraising the lifecycle inventory databases are proposed. Building on the appraisal criteria proposed in Section 4, a comparative analysis of the LCID is presented in Section 5. Section 6 presents the main contribution of this work, proposing the method of integration for the LCID in the early phases of the building lifecycle. The first step of the integration of the LCID, namely the linking of the LCI data with the building data, is examined in Section 7. In section 8, the integration of the LCI data using BIM software and linked building data is illustrated, and some conclusions are drawn in Section 9.

2. State-of-the-art review

2.1. Life Cycle Assessment (LCA) for building construction sector

It is essential to begin by providing a working definition of LCA. This will be followed by an examination of LCA database inventories. The last sub-section will focus on LCA results.

2.1.1. What is LCA?

Life Cycle Assessment (LCA) is defined as a methodological framework (DIN ISO 14040/44 [1]) that can be used to assess environmental impacts associated with all the stages of a product's life from raw material extraction through materials processing, manufacturing, distribution, use, repair and maintenance, and disposal or recycling. Rashid and Yuso [2] define LCA as a methodological framework that can be used for estimating and evaluating environmental impacts throughout a product's life cycle from cradle to grave. LCA can be divided into four steps [1, 2]: Definition of goals and scope, Life Cycle Inventory (LCI) analysis, Life Cycle Impact Assessment (LCIA) and Interpretation. Figure 1 summarizes the activities undertaken in each step.

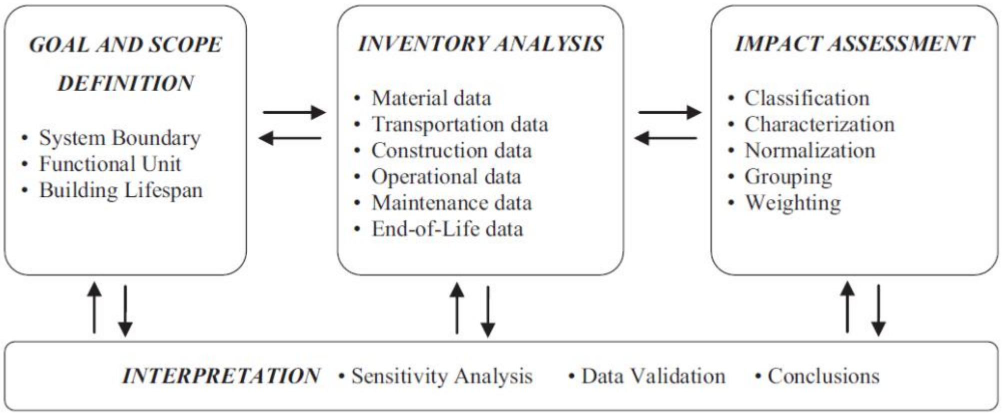

Figure 1: LCA framework for the building industry [2]

Despite a clear distinction between the steps in Figure 1, implementing LCA on buildings is not without challenges, primarily because of their complex nature. Furthermore, any building's lifespan is spread out over time, and the structure is made up of multiple products that deserve specific attention since each has a life cycle of its own (individual product lifecycle versus building lifecycle). The complexity of buildings is also typified by the number of their component parts. For instance, a typical domestic house contains 40,000 parts while, in comparison, an average car has 3,000 (Egan, 1998). Clearly, the high complexity of buildings, especially the multiplicity of their component parts, presents significant challenges to the assessment of their environmental performance.

2.1.2. A review of LCIDs

Many studies have compared or analysed different LCIDs, especially with regards to construction materials. Lasvaux et al. [5] compared two existing LCIDs, namely Ecoinvent, developed in Switzerland, and INIES, the French national reference database for environmental and health data on construction products and equipment. Their study aimed to understand the numerical and methodological differences between the database inventories. Twenty-eight building materials were compared using LCA indicators in the EN 15804 standard, calculated in alignment with Ecoinvent and INIES. The study revealed that deviations of various magnitudes exist depending on the LCID indicators and the building materials. Also, some of the INIES and Ecoinvent indicators are different. In many cases, Ecoinvent indicators were found to be too generic.

Furthermore, in Lasvaux et al.'s [5] study, some building materials showed systematic differences for all lifecycle assessment methods. The authors claim that the differences mainly depend on the environmental indicator and the type of building materials used and that these factors can significantly influence the final environmental performance of a building.

Martınez-Rocamora et al. [6] conducted a literature review of LCID, specifically for construction materials. Their study provided a basis for the selection of LCID for such materials. The LCIDs are divided into three groups: (1) European: Ecoinvent, GaBi Database, European Platform on Lifecycle assessment (ELCD) Database 3.1, (2) American: Athena Database, and (3) national databases: Base Carbone, ProBas, etc. They proposed six main features to aid the comparison of LCID databases. These include scope, completeness, transparency, comprehensiveness, recency and licence, but their study focused on only three aspects: completeness, transparency and comprehensiveness. Martınez-Rocamora et al. [6] found transparency to be the decisive feature in their comparison. Nevertheless, they recommended traceability, comprehensiveness and methodology as key features when comparing two construction materials. Also, Takano et al. [7] conducted a comparative study of five LCID, using three buildings as case studies for their analysis. The databases compared included GaBi (Germany), IBO (Austrian Institute for Healthy and Ecological Building), CFP (Japan Environmental Management Association for Industry/Advanced Industrial Science and Technology), Ecoinvent and Synergia (Finnish Institute of Environment). Furthermore, the study revealed numerical and methodological differences between diverse building lifecycle assessments. The databases were compared on the basis of Greenhouse gas (GHG) emission values in the material production phase of the reference buildings. The authors found that the databases showed similar trends in the assessment results and the same order of magnitude of differences between the reference buildings. Furthermore, numerical differences originated from multiple data elements.

2.1.3. LCA results

The outcomes or results of LCA calculations carried out for a specific product and organized in conformity with the ISO 14025, EN 15804+A1 and XP P01-064/CN standards constitute an Environmental Product Declaration (EPD). This EPD value communicates the environmental performance of a product over its lifetime [3, 4]. Being a Type III eco-label, EPDs are specific to construction products. EPD is a source of clear information regarding each product's performance and environmental impact throughout its entire lifecycle. Furthermore, based on international standards, EPDs are verified by independent examiners.

An EPD database contains a large number of product declarations across one or more countries. The information contained in EPD databases is meant to be used by experts in various sectors including the building, to enable the lifecycle assessment (LCA) of their final product during its lifecycle. However, the applications and uses of EPD databases in construction are fraught with difficulties. Firstly, construction professionals come from different backgrounds with disparate levels of understanding and interest in the practical implementation of EPD and, secondly, there is a lack of interoperability between the different software systems that might be employed in the assessment of environmental impacts using EPD.

2.2. Integration of multiple LCA databases

Many approaches for integrating LCA databases have been tested. These include, for example, Ontology-Based Data Integration (OBDI) from Wache et al. [8] and KARMA from Knoblock et al. [9]. KARMA is better suited to big data integration with semantics [10], and particularly to solving problems of the big data variety [11], or to discovering semantics while leveraging Linked Open Data [12]. Many approaches exist for OBDI: single, multiple or hybrid ontology approaches. Focusing on material data, Schwartz et al. [13] proposed the integration of EPD data using a semantic web approach. They defined the data in the Resource Description Framework (RDF) and combined that data afterwards. However, manually defining instances of EPD data is laborious, subject to human errors, and is likely to be impossible if there is a large amount of data. Furthermore, the transition from 'regular' databases to semantic graph databases based on RDF is typically considered to be far from straightforward.

2.3. Integrating LCA in a BIM environment

Anton et al. [14, 15, 16] proposed two approaches for integrating LCA calculations into BIM applications and workflows. Based on extracting direct project data from the BIM model to perform LCA, the first approach allows the complete construction to be evaluated during its entire lifecycle. The second approach includes LCA-related information in the features of the various BIM objects, which is then used in conducting the LCA. Anton et al. [14, 15, 16] have highlighted some pros and cons of integrating LCA in a BIM environment.

It is essential to keep track of the main environment in which the LCA takes place. In the first approach, if a neutral data exchange format is relied upon, such as the Industry Foundation Classes (IFC), the result is that the LCA calculation takes place *outside* the main design environment, which results in less integration in the (early) design workflow. In the second approach, however, it would be easier to include the LCA *inside* the main design environment through the implementation of services and plugins inside the native modelling software. So, the distance from the design environment with LCA may be shorter in the second approach, and that is valuable for improving the building design process.

2.4. Linked Building Data (LBD)

Linked data, also called the Web of Data, is data available as RDF graphs. It provides an extension of the Web by enabling the sharing and publishing of raw data with the use of open standards [17], namely the RDF data model, Uniform Resource Identifiers (URI), Simple Protocol and RDF Query Language (SPARQL), the Web Ontology Language (OWL), etc. Available data are also linked to each other via URIs. They can subsequently be stored in a triple (i.e. a data entity composed of subject-predicate-object) : a purpose-built database that stores semantic facts in the form of RDF graphs, against which queries can be made in SPARQL [18].

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, software and through the internet. LBD makes use of a set of available vocabularies like Building Topology ontology (BOT) [19], Property set definition ontology (Props) [20], and Product ontology (PRODUCT) [21], to gather and share building data. Many implementations related to LBD have emerged recently [22, 23, 24].

Using three building-based ontologies: BOT, PRODUCT and PROPS, an IFCtoLBD converter was built by Jyrki Oraskari (https://github.com/jyrkioraskari/IFCtoLBD) [23] and allows the conversion of building data into RDF graphs: so-called linked building data. Compared to previous implementations of transforming IFC-based building data into RDF graphs [25, 26, 27, 28, 29, 30], data are not in one monolithic and complex graph, inherited from the equally complex and monolithic IFC standard. Instead, graphs are separated into building elements (according to BOT), products (according to PRODUCT ontology) and property set definitions (according to PROPS). Taking advantage of the opportunity to separate product data from other data (properties and building elements) [23], environmental RDF data can now be more easily integrated into building elements without increasing the complexity of data querying or browsing (modular and loosely linked ontologies).

Since the building lifecycle 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 those wishing to exchange or share information. Costa and Sicilia [31] addressed this challenge by performing several data transformations on generated and available data between input and target ontologies using SPARQL (ontology mapping). However, this method is subject to the limitations of each domain-based format generated.

3. Research methods

In this article, we propose an alternative approach for combining LCA-related datasets to make them appropriately available in BIM tools and processes. Our method(s) are described in Figure 2.

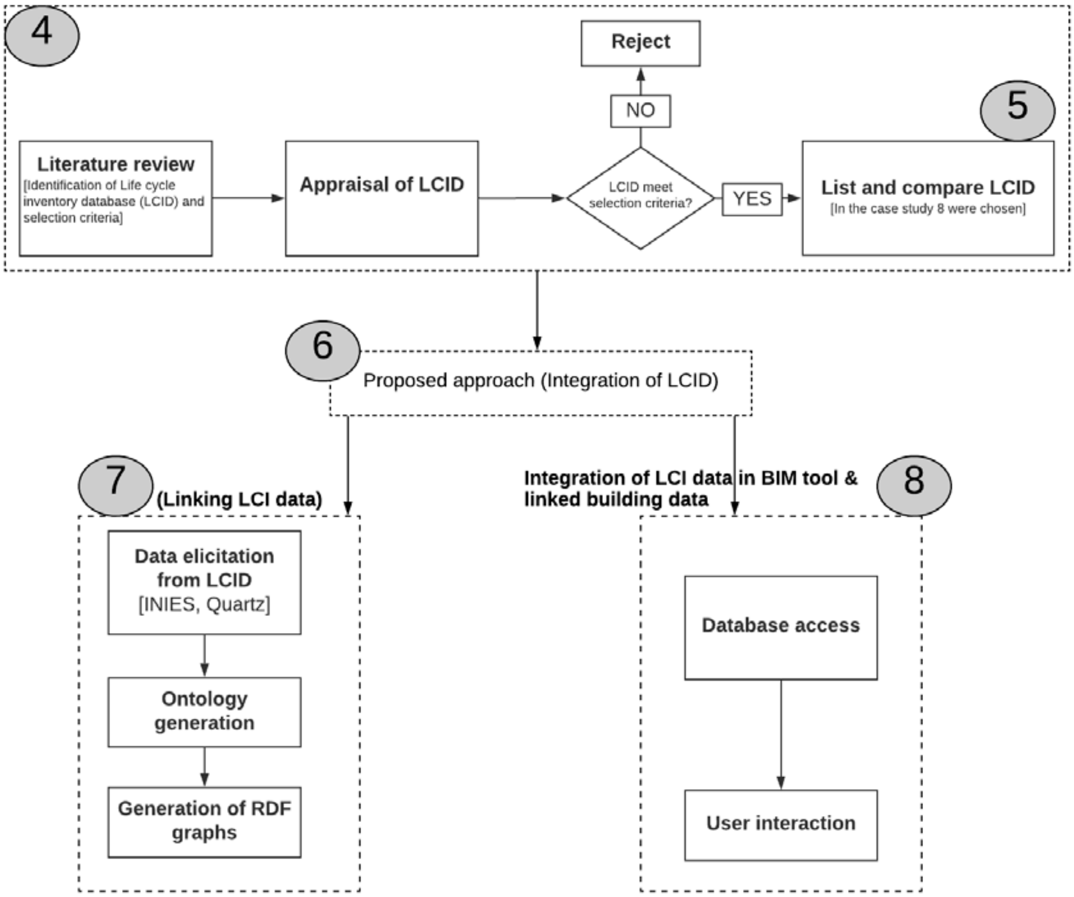

Figure 2: Method Framework

The framework consists of five main steps, named 4, 5, 6, 7 and 8. The process starts with section 4 in alignment with the preceding sections. For clarity, the steps will be described in further detail in the following sections.

4 An Examination of Lifecycle Inventory Databases

4.1. Classification criteria

Based on the literature on building material databases and LCIDs [6], we propose 17 classification criteria categorized in eight groups, as shown in Figure 3. These groups and criteria have been used for reviewing available databases.

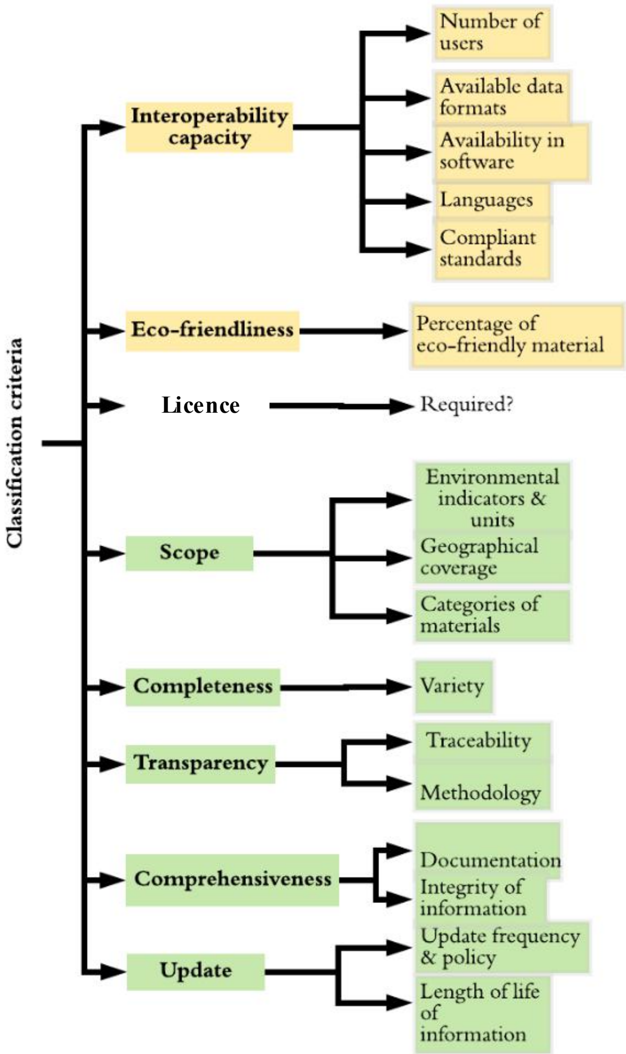

Figure 3: Classification criteria of LCA databases

Scope includes not only the categories of materials studied but also their geographical coverage. Notably, the geographical location where materials are manufactured. Specifically, the following factors are considered as part of “scope”:

- The geographical area covered
- The number of materials included or the size of the database
- The number of categories of materials covered
- The different environmental indicators and their units

Completeness answers the question: “Is every variation of material covered in its category?

Transparency The two factors considered for transparency are traceability and methodology, and deal with questions such as: “What is the methodology used?”, “Is the methodology explained?”, “Is a literature reference associated with the study?”, “What are the boundaries of the study?”, “What are the flaws considered?”

Comprehensiveness measures the level of detail and the integrity of the information provided for each material. It states the extent to which the data entered is based on prevailing standards. The two factors considered for comprehensiveness are the availability of documentation and the degree of confidence accorded to data entered by vendors. It explores questions such as "To what extent is data entered on the basis of prevailing standards?"

Update (Recency) measures the difference between the last update of the database and the date at which it is used for an assessment process. The two factors considered for Update are: the length of life of the information recorded in the database and the update frequency and policy.

Licence indicates whether a licence payment is necessary to access the databases. This criterion refers to the licence type (fee/free), the possibility of relying on an academic licence, and the reliance on commercial or open databases.

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 of the commonly used software on the market?", "In how many languages is the information in the database available?", "Is this information compliant with up-to-date national/international standards?" "How many users does the database have?" Specifically, the following factors are considered as part of interoperability.

- The data format(s) in which data is available: api, sql, pdf, sheets, text, csv, xml, json, etc.
- The compatibility/availability of the database with/in most used software
- The number of users
- The languages used in the database: are the data available in English?
- The standards with which information complies

Eco-friendliness of an LCID specifies the percentage of eco-friendly or biosourced materials it contains.

When a particular building materials database or LCID is being studied, the above criteria are essential to the objective of the study. Before presenting a non-exhaustive list of databases on building materials, we recall that one of the objectives of this study is to identify and coordinate all existing LCIDs, to promote the use of environmentally friendly materials and to encourage sustainable construction. Following the criteria mentioned, we will focus on eight databases: INIES, GaBi, Quartz, Ecoinvent, Bath ICE, Base Carbone, DIOGEN and the International EPD ® System. These databases are used here because they are the ones that include construction materials (scope).

4.2. Using the established criteria to appraise the LCID

4.2.1. INIES

INIES is a French national reference database of environmental and health declarations (HQE-GBC, 2018). INIES contains construction products, equipment and services, evaluating their work performance. INIES is currently only available in French and only used in France. It is a free access database but, unfortunately, on the condition that the user holds a Microsoft Silverlight licence. There is a web service to provide access to digitized data, but it requires payment of a fee. For each product inside the database, image or pdf files are available with data. For building construction, INIES has 2096 records divided into three categories: construction service, construction products and electronic/electrical equipment. 'Building' is the only family in the INIES catalogue. For each category, it provides detailed data for environmental declarations per reporting organization. For each product, INIES provides four important types of information: general information, functional unit, environmental indicators, retrievable documents and sometimes health and comfort information. The environmental indicators comprise environmental impacts, resource consumption and waste.

A weakness can be noted, however: although INIES provides a warning concerning the usage of environmental data, it is generic. Also, an examination of the INIES database reveals that it contains relatively little information about bio-sourced materials such as those made with hemp, wood, straw or clay. For example, for thermal insulation, 14 of the 246 reference materials are from biological sources. Table 1 shows how INIES responds to the criteria of Figure 3.

Table 1: INIES

Scope	Geographical coverage	France
	Categories of materials	Construction services (45), construction products (1457) and Electronic/electrical equipment (916)
	Environmental indicators & units	Four groups containing 26 indicators: environmental impacts, consumption of resources, wastes, outgoing flows.
Completeness	Variety	2418 entries
Transparency	Traceability	Available
	Methodology	Available in each LCI
Comprehensiveness	Documentation	Available
	Integrity of information	AFNOR
Update	Update frequency & policy	weekly
	Length of life of information	5 years
Licence	Required?	Yes
Interoperability capability	Available data formats	Images, PDF & through web services
	Availability in software	Elodie [33]
	Languages	French
	Number of users	Software users & researchers
	Compliant with standards	NF EN 15804+A1
Eco-friendliness	Percentage of eco-friendly material	Contains wood and clay

4.2.2. GaBi

Developed by thinkstep (2018), the GaBi database is an LCID used in several industries, including building construction. The GaBi database contains over 12,000 ready-to-use lifecycle data profiles based on primary industry data. Developed over 20 years ago, the GaBi database is still evolving. The associated search engine 'Gabi Data Search' provides the opportunity to find a specific process or material within the database by specifying one to five criteria.

However, the entire database can only be accessed via GaBi Software. Table 2 shows how GaBi responds to the criteria of Figure 3.

Table 2: GaBi

Scope	Geographical coverage	Over 20 countries worldwide
	Categories of materials	15
	Environmental indicators & units	Many, such as Eco-Indicator 99
Completeness	Variety	3169 processes on construction materials
Transparency	Traceability	Available
	Methodology	Cradle-to-gate
Comprehensiveness	Documentation	Available
	Integrity of information	Verified by Derka
Update	Update frequency & policy	Annually
	Length of life of information	6 years
Licence	Required?	Yes
Interoperability capability	Available data formats	PDF & XML
	Availability in software	GaBi Software Suite
	Languages	English
	Number of users	10000
	Complies with standards	ISO 14044, ISO 14064 and ISO 14025
Eco-friendliness	Percentage of eco-friendly material	Contains wood and clay

4.2.3. Quartz database

Developed by Google, Healthy Building Network, FLUX, thinkstep, and other companies, the Quartz Common Product database is a building material database. Presently, the database contains 102 products with the following information:

- A description
- The general composition of the product
- The impurities contained
- The health profile: aggregation of potential health hazard
- The environmental profile: LCA results of an ISO 14044 compliant ***quoi?*** (*manque le nom*)
- Some sources: mainly documents and literature referenced.

A major weakness of Quartz is the small number of materials it contains compared to the number of products needed to provide alternative options for use to ensuring that buildings are sustainable. Table 3 shows how Quartz responds to the criteria of Figure 3.

Table 3: Quartz

Scope	Geographical coverage	worldwide
	Category of materials	Construction products

	Environmental indicators & units	6 environmental indicators given in 3 life cycle phases
Completeness	Variety	102 entries
Transparency	Traceability	Sources available
	Methodology	Available for each product
Comprehensiveness	Documentation	Available
	Integrity of information	Manufacturer, patents and trade documents are available
Update	Update frequency & policy	Last release in January 2019
	Length of life of information	No limit
Licence	Required?	Not required
Interoperability capability	Available data formats	JSON
	Availability in software	No
	Languages	English
	Number of users	Not declared
	Compliant with standards	ISO 14044
Eco-friendliness	Percentage of eco-friendly material	Contains wood

4.2.4. Ecoinvent

The Swiss LCID Ecoinvent provides documented process data for many products to inform users about their environmental impact. It covers many countries and sectors, such as construction materials, manufacturing, agriculture and energy. EcoInvent 3.6 is the latest version, and it builds on all previous versions of the database. It is integrated into SimaPro 8 and GaBi 5 software (Martínez-Rocamora et al., 2016). Furthermore, Ecoinvent is compliant with ISO 14040 and 14044. Over 2500 updated datasets have been added to its latest version in diverse sectors, including some for building and refractory materials. Table 4 shows how Ecoinvent responds to the criteria of Figure 3.

Table 4: ecoinvent 3.4

Scope	Geographical coverage	Europe
	Categories of materials	construction materials, manufacturing, agriculture and energy
	Environmental indicators & units	Many indicators (such as IPPC GWP 100a – Kg CO_2-Eq)
Completeness	Variety	+13300 LCI datasets
Transparency	Traceability	Available
	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
Licence	Required?	Yes
	Available data formats	N.A

Interoperability capability	Availability in software	SimaPro 8 and GaBi 5
	Languages	English
	Number of users	N.A
	Compliant with standards	ISO 14040 and 14044
Eco-friendliness	Percentage of eco-friendly material	Contains wood

4.2.5. Bath ICE

The Inventory of Carbon and Energy (ICE) was developed by the Sustainable Energy Research Team (SERT) of the University of Bath and is known as Bath ICE. Bath ICE provides profiles of more than two hundred building materials. The environmental parameters for assessing the performance of construction materials are embodied energy and embodied CO_2. Using the assessment criteria, Bath ICE is presented in Table 5.

Table 5: Bath ICE

Scope	Geographical coverage	UK
	Categories of materials	34
	Environmental indicators & units	Embodied energy, total CO_2
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
Licence	Required?	No
Interoperability capability	Available data formats	HTML (web) access to Excel or PDF file
	Availability in software	None
	Languages	English
	Number of users	N.A
	Compliant with standards	ISO 14040/44
Eco-friendliness	Percentage of eco-friendly material	Contains wood

4.2.6. Base Carbone

Managed by the French Environment and Energy Management Agency (ADEME), Base Carbone is a French database that aims to enable carbon emissions to be recorded. Data contains categories of products for France (ADEME, 2018a; 2018b). However, the LCID is not open, as it requires a licence. The assessment of Base Carbone vis-à-vis the assessment criteria of Figure 3 is presented in Table 6.

Table 6: Base Carbone

Scope	Geographical coverage	France
	Categories of materials	12
	Environmental indicators & units	Greenhouse gas emission - CO_2 kilograms per ton
Completeness	Variety	+1300 materials
Transparency	Traceability	Insufficient
	Methodology	Cradle-to-grave
Comprehensiveness	Documentation	Provided but externally
	Integrity of information	N.A
Update	Update frequency & policy	April 2016
	Length of life of information	3 years
Licence	Required?	Yes
Interoperability capability	Available data formats	CSV
	Availability in software	None
	Languages	French
	Number of users	N.A
	Compliant with standards	-
Eco-friendliness	Percentage of eco-friendly material	Contains wood

4.2.7. DIOGEN

Données d'Impact pour les Ouvrages de GENie Civil (DIOGEN) is an open-access French database (Peuportier, 2016). Using the same methodology as Ecoinvent, it is a cradle-to-gate environmental database that provides impacts of production materials used in France for civil engineering projects. DIOGEN contains five categories and 44 materials. For each product, the available information includes name, description, number of downloads, and a downloadable file. Each file contains a product described by confidence index, environmental impacts according to standard NF P01-010, complementary environmental impact, references, technological assumptions and an environmental information module. The assessment of DIOGEN vis-à-vis the assessment criteria of Figure 3 is presented in Table 7.

Table 7: DIOGEN

Scope	Geographical coverage	France
	Categories of materials	5
	Environmental indicators & units	MJ, Kg, kg eq. Sb, Kg eq. CO_2, Kg eq. SO_2, 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	Documentation
	Integrity of information	Verified by an AFNOR certified auditor
Update	Update frequency & policy	2013

	Length of life of information	No limit
Licence	Required?	Free - subject to registration
Interoperability capability	Available data formats	HTML and PDF file
	Availability in software	CIOGEN software
	Languages	French
	Number of users	Users of CIOGEN + others
	Compliant with standards	NFP01010 then EN 15804
Eco-friendliness	Percentage of eco-friendly material	Contains wood

2.8. The International EPD® System

In addition to the databases presented in the preceding section, there is an international system of Environmental Product Declarations (EPD), called the International EPD® System [41], for a wide range of product categories. These categories include: construction products, paper products, furniture, textile, footwear, infrastructures and buildings, and chemical products, among others. However, the amount of data in the building category is very poor. For instance, only 16 products and services concerning the building and infrastructure category are identified in the system; and they are mainly about railways, bridges or roads. For the construction products category, there were 654 EPDs available at the time of writing.

The EPD for each product contains interesting, 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 lifecycle. Table 8 gives an overview of the assessment of this database according to our evaluation criteria.

Table 8: International EPD R System

Scope	Geographical coverage	Worldwide
	Categories of materials	More than 10 categories of materials
	Environmental indicators & units	7 environmental indicators given in 4 life cycle stages
Completeness	Variety	899 entries for construct product category
Transparency	Traceability	Sources available
	Methodology	Available for each product
Comprehensiveness	Documentation	Available
	Integrity of information	Sources available for each product
Update	Update frequency & policy	Last release in 2020
	Length of life of information	5 years and stated for each product
Licence	Required?	Not required
Interoperability capability	Available data formats	HTML, PDF & QR code

	Availability in software	Framework to create machine-readable EPD files available
	Languages	English, Spanish
	Number of users	Not declared
	Compliant with standards	EN 15804 (892 of 899) and stated for each product
Eco-friendliness	Percentage of eco-friendly material	Contains wood

5. Classification of LCIDs

The comparison will focus on INIES, GaBi, Bath ICE, Ecoinvent, DIOGEN, Quartz, Base Carbone and the International EPD® System. The basis of the comparison will be the criteria discussed in the preceding section, including scope, completeness, transparency, comprehensiveness, update, i.e. recency, and licence, with the addition of interoperability capacity and eco-friendliness as comparison criteria. The scoring system proposed by Martınez-Rocamora et al. [6] will be used.

- (N.A) the information is not accessible
- (-) the criterion is not met in the database
- (+) the database partially or sometimes satisfies the criterion
- (++) the criterion is satisfied at a low level
- (+++) the database completely satisfies the criterion

Using this rating system, the score for each criterion can be computed for each LCID. As an example, for the Quartz database, we attributed +++ to the three sub-criteria, leading to a total of 9+. An average was then computed, which led to the value of +++ as shown in the Average score column of Table 9. However, it is important to note that the criterion values with N.A. and (-) are excluded from the computation of the averages. Also, geographical coverage is awarded a rating of (+++), if it covers at least one country. Lastly, the average values are rounded to the nearest whole number.

Table 9 : Score of Quartz vis-à-vis appraisal criteria

Criterion	**Sub-criterion**	**Criterion value**	**Score**	**Average score**
Scope	Geographical coverage	worldwide	+++	+++
	Category of materials	Construction products	+++	
	Environmental indicators & units	6 environmental indicators precise in 3 life cycle phases	+++	
Completeness	Variety	102 entries	+	+
Transparency	Traceability	Sources available	+++	+++

	Methodology	Available for each product	+++	
Comprehensiveness	Documentation	Available	+++	+++
	Integrity of information	Manufacturer, patents and trade documents are available	+++	
Update	Update frequency & Policy	Last release in January 2019	+	+
	Length of life of information	No limit	++	
License	Required?	Not required	+++	+++
Interoperability capability	Available data formats	JSON	+++	++
	Availability in software	Not being used by other software	-	
	Languages	English	+++	
	Number of users	Not declared	+	
	Compliant standards	ISO 14044	+++	
Eco-friendliness	Percentage of eco-friendly material	Contains wood	+	+

The average scores for the performance of the LCIDs vis-à-vis the appraisal factors, found by implementing the procedure in the preceding paragraph, are presented in Table 10.

Table 10: Comparison of LCID

	INIES	GaBi	Bath ICE	EcoInvent	DIOGEN	Quartz	Base Carbone	International EPD System
Scope	+++	++	+++	++	++	+++	+++	++
Completeness	+++	+++	+++	++	++	+	+++	+++
Transparency	++	+++	+++	+++	+	+++	+	+++
Comprehensiveness	+++	+++	+++	+	+++	+++	++	+++
Update	++	+++	++	++	++	+	++	+++
Licence	-	-	-	-	-	+++	+++	+++
Interoperability capability	++	++	++	++	++	++	+	++
Eco-friendliness	++	++	+	+	+	+	+	+

The LCIDs were compliant with national and international standards like ISO 14001:2004 NSAI IQNet Certified, ISO14044, DIN EN 15804, and NF EN 15804+A1. These standards mostly concern environmental metrics and EPD. Based on the rating of the LCIDs in Table 10, it can be concluded that:

- Bath ICE and DIOGEN are the two LCIDs that focus on building construction materials only, while the others are more general and cover more.

- The International EPD System had five (+++) ratings, followed by Quartz and Bath ICE with four (+++) ratings. The fact that the International EPD System got the highest rating of +++ is not surprising as it contains independently verified EPD.
- Interoperability is one of the weakest parameters, with no +++ rating.

It is against this background that we propose a methodology that can permit the seamless communication or integration of LCIDs, which will enhance interoperability. To achieve this, we chose to rely on the INIES and Quartz databases, which contain more than just construction materials. Both these LCIDs are generic and serve better as test cases than specialized or focused LCIDs such as Bath ICE and DIOGEN. The methodology is presented in Section 6.

6. Method for integration of LCIDs

When the aim is to enhance sustainability in building construction, improving the way products are chosen during the lifecycle of the building is of critical importance. Following the argument in the literature (Section 1), the enhancement could be made through the use of semantic web technologies such as RDF, SPARQL, etc. The section below details our proposed approach towards achieving linked data-oriented integration. Very importantly, instead of reverting fully to an RDF-only approach, as is often seen in the literature, this work attempts to perform the data integration by making an apt combination with more regular web technologies and stacks, including JSON-based APIs.

To achieve these aims, data was first gathered from the chosen LCID, from which three OWL ontologies were generated. Using the latter, data were translated from their original format, XML and JavaScript Object Notation (JSON) formats, to RDF graphs. This step could be automated to allow the proliferation of legacy database systems often used for these LCIDs (e.g. relational SQL databases).

To address the issue of accessibility of products and their simultaneous environmental assessment by users during the whole building lifecycle, and particularly in the design phase, we extend an existing BIM tool by adding a plugin to upload product data directly from an LCID triplestore that contains the resulting RDF data. Using our plugin through the user interface (UI) of the BIM tool, it is then possible to generate LBD graphs for a complete building, containing the relevant LCA data. The overall method is described in Figure 4, with details explained in Sections 7 and 8.

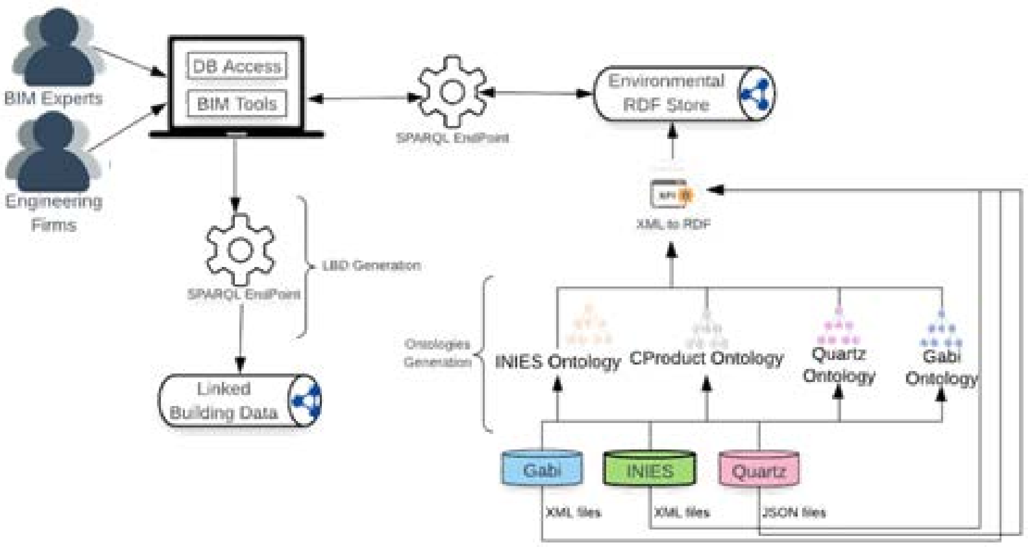

Figure 4: Framework for the integration

On the right side of the framework, using a Java Application Programming Interface (API), OWL ontologies are first generated from the available environmental data. Then, environmental data from INIES and Quartz are translated from XML or JSON to RDF graphs and stored in a triple-store, compliant with the available OWL ontologies. The left side of the diagram shows a plugin that was developed and installed in a BIM tool to enable access to the environmental data by a BIM modeller, directly from its design environment. During or at the end of the modelling phase, users can generate LBD graphs and store them in a triple store for access by other stakeholders. Note that we have shown more than INIES and Quartz in Figure 4, just to indicate that many other LCIDs could be part of the framework.

7. Making LCI data available as linked data

To make environmental data available as RDF graphs, data is first gathered from LCID, then, using nomenclature data, corresponding ontologies are generated. Nomenclature data contains a classification of construction products. Finally, using the ontologies generated, environmental data are translated from their custom formats into RDF graphs. This translation procedure has been developed in one Java program. The following paragraphs present each step of this process.

7.1. Gathering data from EPD databases

7.1.1. 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 [32]. 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 licence was used to access the INIES Web Services (IWS) needed to implement the method presented [46]. The round trip of sending requests and receiving responses, using Simple Object Access Protocol (SOAP), made it possible to gather INIES data in the form of XML files. Each file contains the response for the corresponding sent request. After the login, the GetNomenclature request is sent to gather the entire nomenclature tree used in INIES (Listing 1).

```
<soap:Envelope xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xmlns:xsd=
    "http://www.w3.org/2001/XMLSchema" xmlns:soap="http://schemas.xmlsoap.org/
    soap/envelope/">
    <soap:Body>
        <GetNomenclature xmlns="http://tempuri.org/">
            <SessionID>T4tLynnBJE</SessionID>
        </GetNomenclature>
    </soap:Body>
</soap:Envelope>
```

Listing 1: GetNomenclature request

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 that is another item. “Bois massif” is one of the nomenclature items in the INIES database. Its XML serialization is presented in Listing 2.

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

Listing 2: GetNomenclature response - the 153 Nomenclature Item and its parent

7.1.2. Quartz

Quartz is a Worldwide EPD database. Its data is available free of charge online, either in a single but not detailed Microsoft Excel Open XML Format Spreadsheet (XLSX) file, or in several detailed JSON files. JSON files were exploited in the context of this work. Figure 5 presents the contents of a single file in the Quartz database.

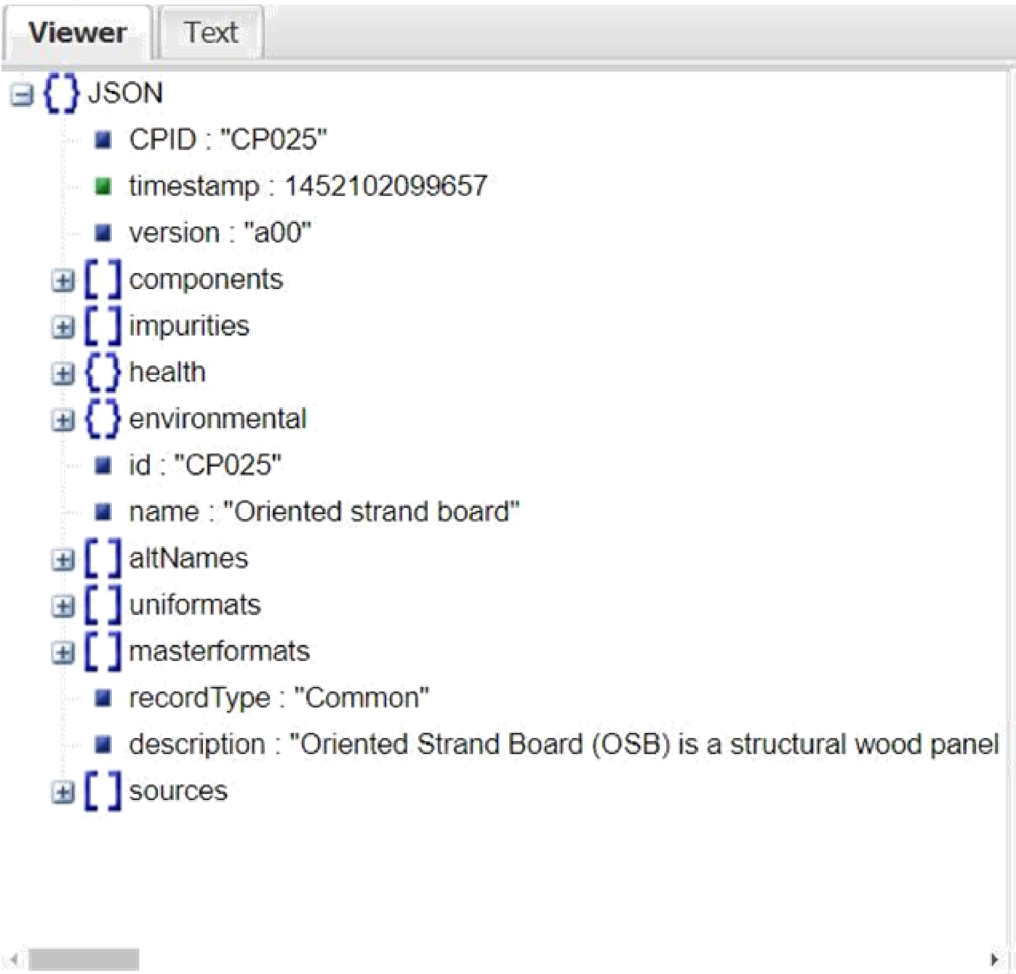

Figure 5: Content of the JSON file of the construction product “Oriented strand board” in Quartz database.

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. Single bullets represent construction product attributes: CPID, version, description, etc. JSON objects are represented with braces and have characteristics: environmental and health. Finally, JSON arrays are represented with square brackets and can contain a list of JSON objects or a list of JSON arrays: components, sources, etc.

The JSON file shown in Figure 5 contains the lifecycle information about the product named “Oriented strand board” for which the identifier is “CP025”. Since all files in the Quartz database have a similar structure, a Java program named “CustomReadJSONFile” was developed to read all of them and make their content available for the following steps of our method.

7.2. Ontology generation

7.2.1. Generation of CProduct ontology

Using Apache Jena [47] in a Java API, the GetNomenclature XML file was used 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 the 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 [21].

7.2.2. Generation of INIESOnto

The CProduct ontology is based on the INIES nomenclature and excludes properties; it is solely a taxonomy of terms. To generate an ontology with the properties contained in the INIES data, termed INIESOnto here, the GetAllFDESFullDataByID request was sent to obtain all data contained in each FDES or about a specific product by explicitly stating its ID.

```
<soap:Envelope xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xmlns:xsd=
    "http://www.w3.org/2001/XMLSchema" xmlns:soap="http://schemas.xmlsoap.org/
    soap/envelope/">
<soap:Body>
    <GetFDESFullDataByID xmlns="http://tempuri.org/">
     <FDES_ID>4156</FDES_ID>
        <SessionID>ipI7R65GPC</SessionID>
    </GetFDESFullDataByID>
</soap:Body>
</soap:Envelope>
```

Listing 3: GetAllFDESFullDataByID response - the 4156 FDES data

As a result of this request for any product (see Listing 3 for the product with ID=4156), all available data on life cycle assessment of the product were obtained and stored in an XML file. This included a list of constituent products, health data, a set of quantity gauges, etc. Using the XML file, the INIESOnto ontology was then generated with our Java API. As can be seen in Figure 6, the INIESOnto contains all properties that can be found in all FDES files.

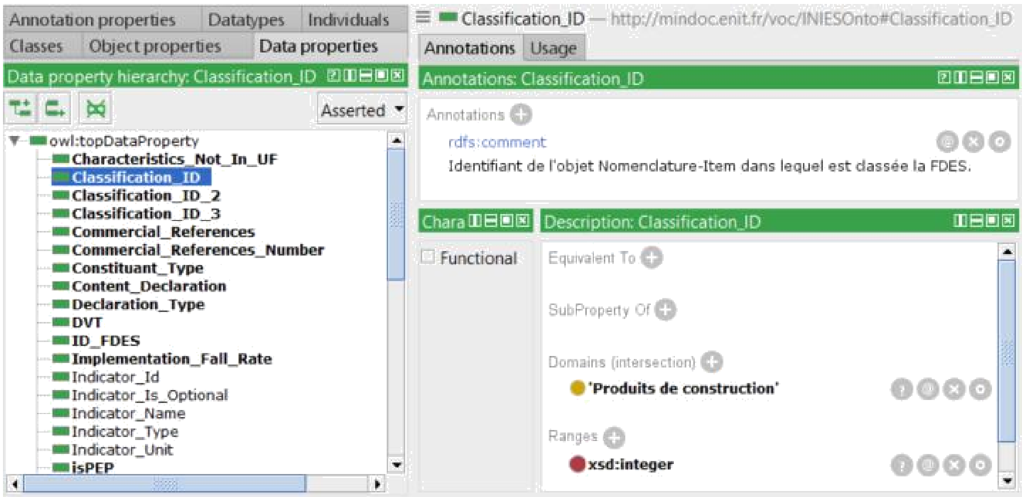

Figure 6: INIESOnto

The INIESOnto is defined by prefix fdes and URI http://mindoc.enit.fr/voc/INIESOnto. Containing only data properties that are specific to INIES, INIESOnto is generated separately from CProduct ontology but imports it. This means that INIESOnto contains all concepts and relations from CProduct ontology. Furthermore, each entity (OWL class, object or data property) created in INIESOnto is aligned to a corresponding one in CProduct ontology where possible.

7.2.3. Generation of QuartzOnto

To generate the Quartz ontology (QuartzOnto), a similar approach was followed, relying on the different data infrastructure in the Quartz database. A JSON file is randomly chosen in the Quartz database, and its content is read. Each characteristic of the product that is directly available becomes a data property in QuartzOnto. As depicted in Figure 5, CPID, timestamp, version, ID, name, recordType and description become data properties. Also, each object of the JSON file causes the creation of an OWL class. Thus, Environmental and Health classes are created in QuartzOnto.

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 to the corresponding one in CProduct ontology where possible. Figures 7 and 8 present QuartzOnto entities. QuartzOnto has as preferred prefix: quartz and the URI http://mindoc.enit.fr/voc/QuartzOnto.

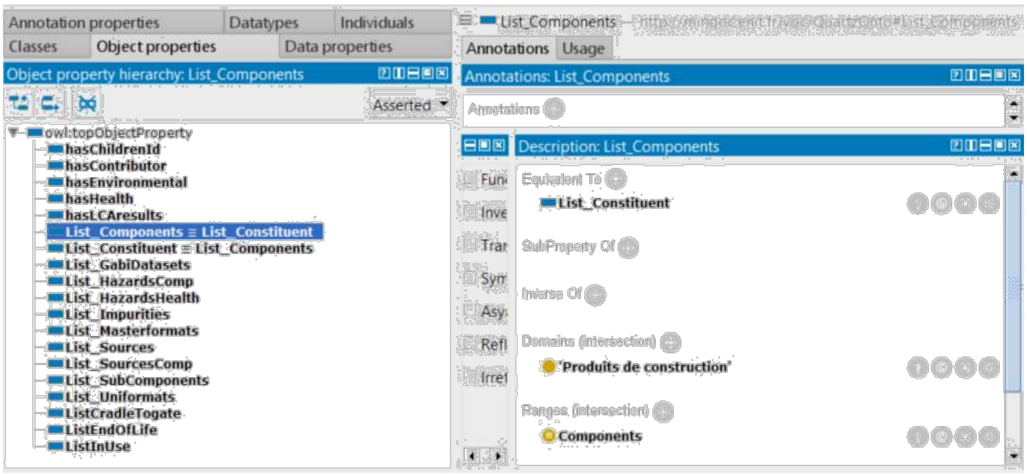

Figure 7: QuartzOnto - Object properties

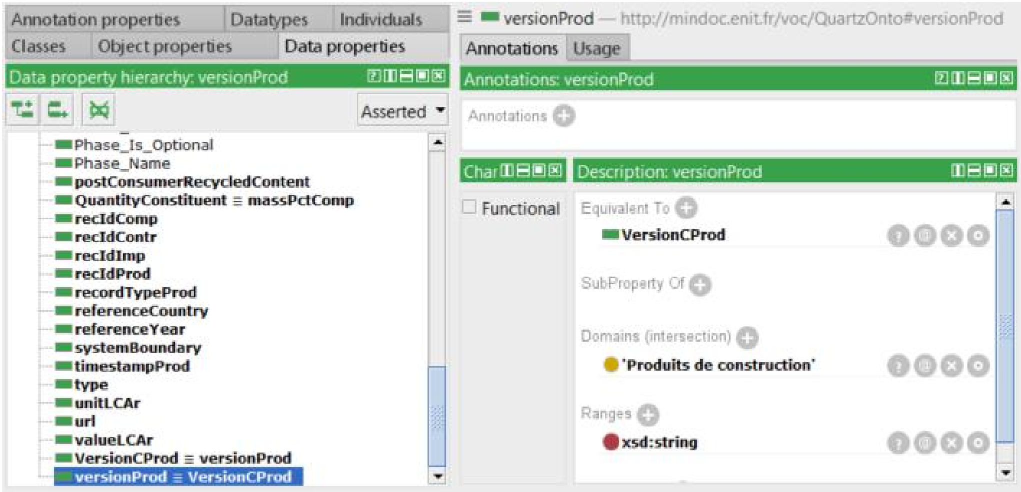

Figure 8: QuartzOnto - Data properties

7.3. From data existing in databases to RDF graphs

7.3.1. 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 9. Figures 10 and 11 present part of the data generated from INIES and Quartz databases respectively.

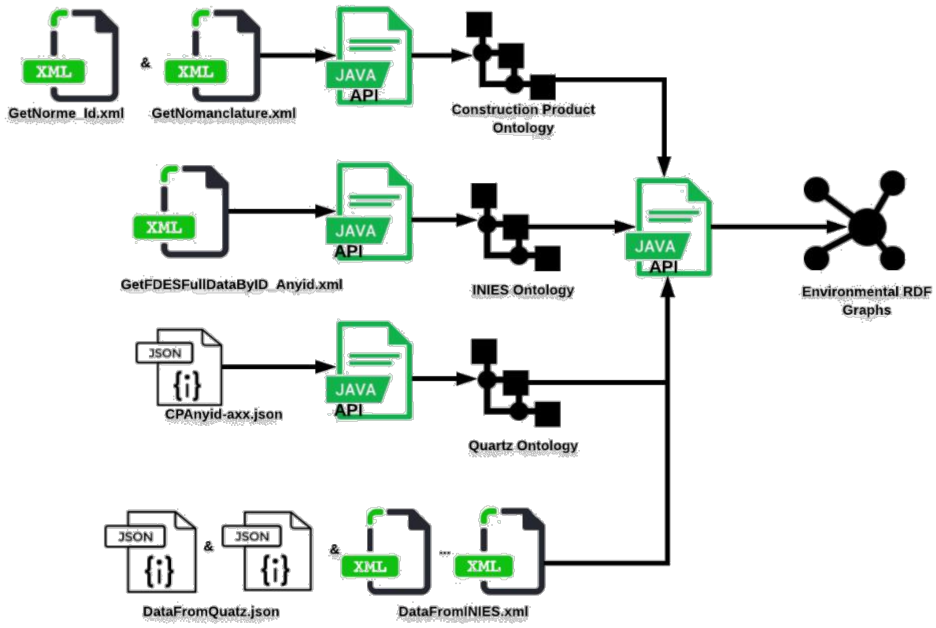

Figure 9: Generating Environmental RDF Graphs with ontologies & Java API.

Using GetNomenclature.xml and GetNorme_id.xml files, Construction Product ontology was generated. Any JSON file from Quartz and any XML file from INIES was used to generate QuartzOnto and INIESOnto respectively. Using the three preceding ontologies, data from Quartz and INIES databases were translated from their original format (JSON and XML respectively) into RDF graphs.

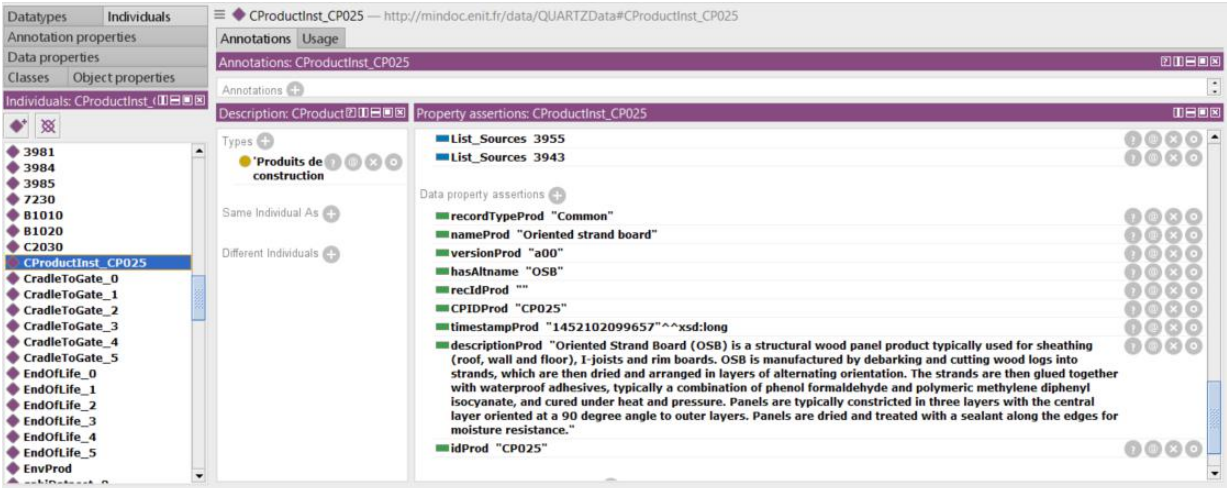

Figure 10: Translating INIES data into RDF Graphs with ontologies & Java API. The URI used is http://mindoc.enit.fr/data/FDESData#CProductInst_4156

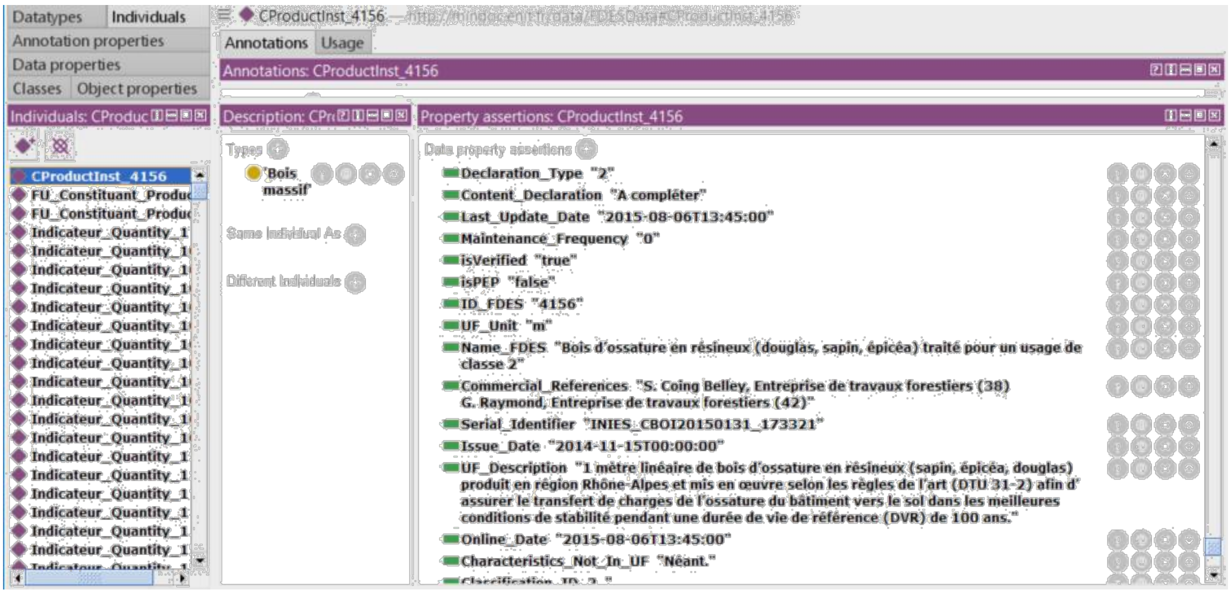

Figure 11: Translating Quartz data into RDF Graphs with ontologies & Java API. The URI used is http://mindoc.enit.fr/data/QuartzData#CProductInst_CP025

7.3.2. Storage of data

Once generated, environmental RDF graphs were stored in a Stardog triplestore. Developed in Java, Stardog is a knowledge graph platform that enables the storage of multiple triples with its Stardog server [48]. Using SPARQL, stored data can be queried and updated through desktop, web or command line user interface, as depicted in Figure 12.

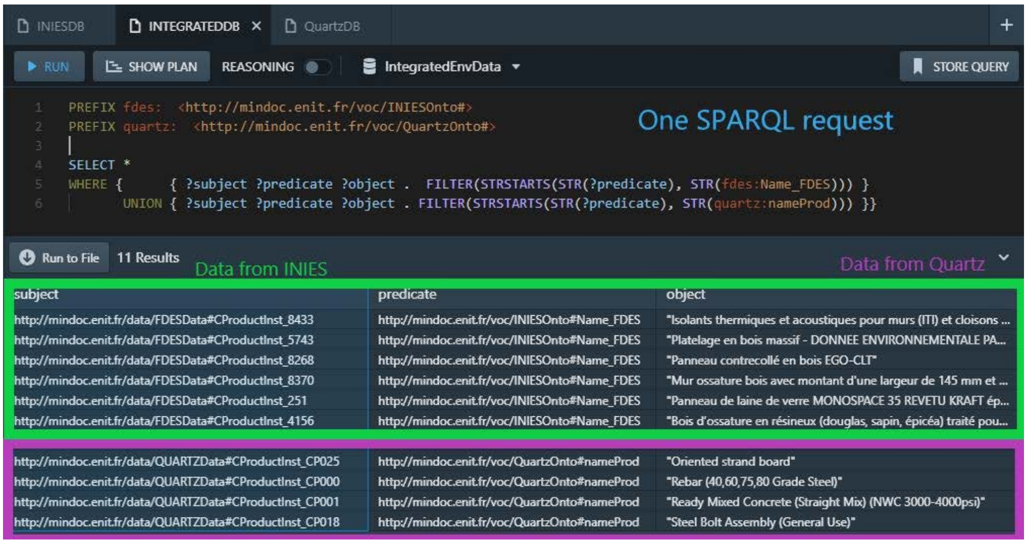

Figure 12: Environmental RDF graphs are stored in a triple-store in Stardog Server and are queried with SPARQL

In addition, APIs like dotNetRDF library [49] were used to interact directly with the Stardog server once it was launched. dotNetRDF is an open source .NET library to parse, manage, query and write RDF, and also to access RDF triple-stores like Stardog or Jena through various user interfaces (UI). An ontology of construction products has been generated: the CProduct ontology. Importing CProduct, the INIESOnto hold characteristics of each construction product as described in INIES database. Using the two ontologies with MINDOC-Revit plugin, our proposed plugin, any XML file resulting from the INIES Web Service and containing environmental data about a particular construction product can be translated into RDF graphs and stored in a triple-store.

8. Integration of environmental data in BIM tool

To properly conduct an environmental building assessment by taking advantage of our environmental RDF graphs in a flexible way, users need an opportunity to choose products easily through their usual interface, preferably any BIM authoring software. The objective of the following section is to present the implementation of our method to enable “Linked” LCID database access in a BIM tool and the generation of LBD embedded with environmental data.

8.1. Database access

Amongst many existing BIM tools used in the design phase of a building life cycle, Revit [50, 51] was chosen for the purposes of this study as Rasmussen et al. [52] have developed a plugin to generate and export LBD graphs from Revit. After adding URI and HOST parameters to each Revit project, the program generates a BOT-compliant Turtle file for the building itself, and also Turtle files for properties, product classes and geometries. The URI parameter in Revit is a URI assigned to each construction product on the Revit UI and HOST is the URI of the construction project in Revit.

In order to meet our plugin requirements, 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 triple store of environmental data. This parameter is added to our plugin that is an extension of the plugin developed by Rasmussen et al. [52]. The aim of this parameter is to store the URI of the product chosen by a user so that we can later query all LCA information about each product of 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 scenes, the program queries the triple store 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 13.

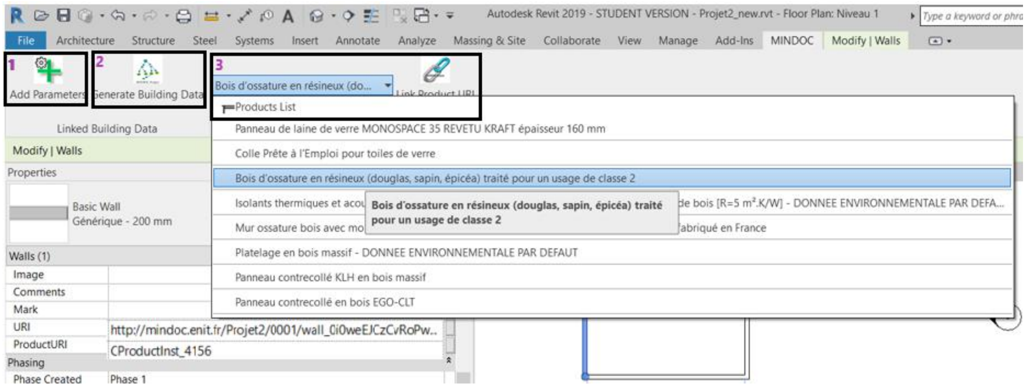

Figure 13: Product List in Revit UI

8.2. User interaction

Our plugin adds a tab called "MINDOC" to Revit UI. The UI of the MINDOC tab is divided into three main features: the addition of parameters to the project (see the left side of Figure 13), the product selection (see the right side of Figure 13) and the generation of LBD graphs. During the modelling, users should click on the "Add Parameters" button to add URI and ProductURI to each element of the project and a HOST parameter to the project itself. Once they have been added, corresponding values adapted to the project needs can be assigned to them.

For the product selection, users select an element of the building, then also select the product to which they want to associate a product classification from the databases. Finally, they click on the button "Link Product URI" to assign the product URI to the ProductURI parameter of the selected element. Behind the scenes, the program finds the URI of the selected product and assigns it to the ProductURI parameter of the selected element. Figure 13 (see the drop-down list on the right) shows how products from the triple store are accessible from the UI.

When the modelling is complete, users click on "Generate Building Data" in order to generate the linked building data of their building. As described in Figure 14, users have the choice of either saving data in several Turtle files or dumping data into the designated triple store; then, the program generates the linked building data. For the first choice, linked building data is stored in several Turtle files. In the case where data are dumped to a triple store (e.g. Stardog), the triple store is updated with the generated linked building data, and data can further be queried with SPARQL requests through a web page, the Stardog studio desktop application or the Windows command line UI.

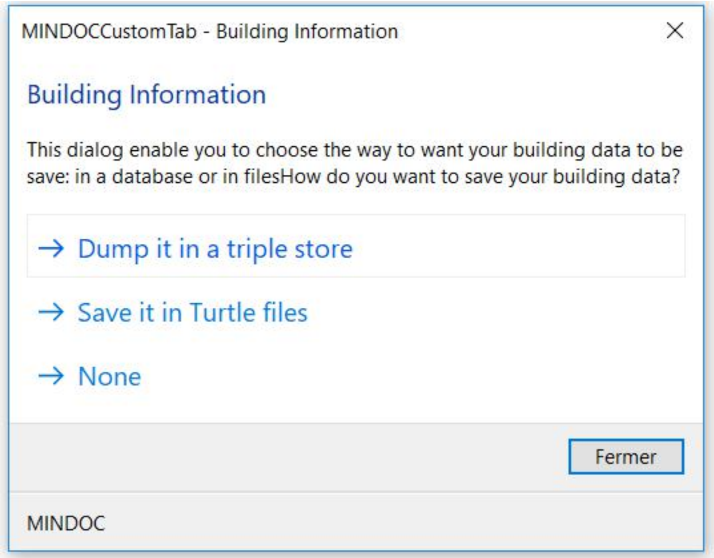

Figure 14: Generate LBD UI Dialog

9. Discussions and Conclusion

This study commenced by establishing the criteria for the classification of LCIDs. The criteria were used to appraise the various LCIDs. It emerged that the limited interoperability of LCIDs, especially with regards to BIM software, hindered efficient exchange or sharing of information between BIM and LCID end-users. It was against this backdrop that a framework for integrating LCID with BIM tools was proposed. The proposed framework revealed that making environmental data available as RDF graphs and also integrating them into a BIM tool could significantly improve the flexibility with which data can be gathered and shared during the building lifecycle. Introducing environmental data at the early stages of a building project also fosters the availability of data for conducting an environmental assessment of buildings in a flexible way [53-58].

In this work, three ontologies have been generated semi-automatically: 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 building life cycle. These results constitute evidence that our proposed methodology proves that semantic web technologies can be used to address data integration challenges in construction practice. Clearly, the approach presented here needs to be scaled up. Where our proposed approach contains several semi-automatic steps (conversion and data transfer), an industry-wide solution needs database suppliers and BIM tool developers to work together more closely and ensure that data connections and transformations are automated in real-time. In other words, the information available upon the integration of INIES and Quartz databases is static here and hence needs to be made dynamic, which can be done by building on the MINDOC-Revit plugin, our proposed plugin.

Specifically, building on the MINDOC-Revit plugin to virtually integrate many LCIDs, which can take updates from each database into account, is a reasonable path for future research. Furthermore, this study can serve as a basis for future research in Digital Twin infrastructures and provision of manufacturers' data, which has been reinvigorated and is gaining interest in the construction industry. The Semantic Web representation of LCIDs is a digital reference that can serve as a basic foundation for building a digital twin for sustainability assessment of buildings. This will be explored as part of our future research.

10. **Acknowledgments**

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