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A Core Ontology for Whole Life Costing in Construction Projects

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Abstract

Construction projects still face persistent barriers to adopting whole life costing (WLC), such as fragmented data, a lack of standardization, and inadequate tools. This study addresses these limitations by proposing a core ontology for WLC, developed using an ontology design science research methodology. The ontology formalizes WLC knowledge based on ISO 15686-5 and incorporates professional insights from surveys and expert focus groups. Implemented in web ontology language (OWL), it models cost categories, temporal aspects, and discounting logic in a machine-interpretable format. The ontology's interoperability and extensibility are validated through its integration with the building topology ontology (BOT). Results show that the ontology effectively supports cost breakdown, time-based projections, and calculation of discounted values, offering a reusable structure for different project contexts. Practical validation was conducted using SQWRL queries and Python scripts for cost computation. The solution enables structured data integration and can support decision-making throughout the building life cycle. This work lays the foundation for future semantic web applications such as knowledge graphs, bridging the current technological gap and facilitating more informed and collaborative use of WLC in construction.

Keywords: emerging technologies; digital data; ontology; whole life costing; building information modelling (BIM)

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1. Introduction

Construction projects are complex in nature, and are therefore subject to significant uncertainties, influenced by a variety of factors that are sometimes beyond control. Recently, the COVID-19 pandemic has highlighted the vulnerability of supply chains and the unpredictability of costs associated with labor, materials, equipment, financing, and insurance [1]. Broad sources of uncertainty, from data scarcity [2] to construction execution quality [3], and long-term uncertainties, concerning energy usage and environmental impact throughout the building life cycle [4], continuously pose challenges to stakeholders. Consequently, long-term vision techniques such as multi-objective optimization methods have gained importance in terms of supporting decision-making systems that encompass a diverse range of interrelated factors [4]. Moreover, uncertainty simulation tools facilitate the modelling of alternative scenarios, thereby aiding project planning [3]. Additionally, risk assessment methods contribute to the quantification of uncertainties and facilitate the identification of potential consequences associated with decisions [2].

Early budgeting is thus increasingly required to be precise, and, in the actual context, is therefore essential to guarantee the economic viability of a project, and to ensure effective cost monitoring throughout the project. Budget management in the construction sector represents a major challenge, particularly when it is based on short-term planning. This short-sighted approach, although commonplace, causes several problems not only for projects but, above all, for investors. Underestimates can lead to overruns during the project due to inadequate planning and changes and delays in payments, which in turn also exacerbate these overruns [5]. Short-term cost-cutting often results in lower quality choices for projects. This trend is persistent in projects, which are still predominantly awarded according to the “lowest-bid” criterion, potentially damaging the financial viability of projects [6]. The economic situation makes things difficult, as each stakeholder suffers from inflation and fights for its own interests to ensure the survival of their companies. In fact, the sector is made up mainly of small and medium-sized companies, which struggle to compete with larger groups. The result is a fragmentation of the industry, hampering efficiency and driving up project costs [7]. Faced with these challenges, the digitalization has the potential to improve the construction sector’s productivity, efficiency, quality, and collaboration through digitization and automation. This turning point is reflected in the growing interest towards building information modeling (BIM) and product lifecycle management (PLM) [8]. BIM, at the center of this digitalization, is defined by ISO 19650-1 2018 [9] as the “use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions”. PLM, often related to the life cycle management (LCM) approach, aims to optimize environmental, social, and economic performance throughout the life cycle of a product or service [10].

This study focuses on the economic aspect of LCM through the whole life costing (WLC) approach. In its simplest form, WLC is made up of present and future costs [11]. WLC is a “methodology for systematic economic consideration of all cost and benefits over a period of analysis, as defined in the agreed scope” [12]. Since its first applications, this approach has been used to determine the best alternatives for projects [13]. The approach can therefore be seen as a sustainable design method, counterbalancing the fact that environmental solutions are often economic obstacles, especially in the short term. Through its life-cycle approach, WLC makes it possible to link the sustainable aspect to the economic aspect, and thus to demonstrates the real implications of investment costs [14]. In this way, WLC can be used as a decision-making tool to help select alternative projects, designs or construction elements, as well as a tool for predicting maintenance and operating costs [15]. A previous study concluded that BIM can bring many technological advantages enhancing WLC [16]. Alsamari [17], conducted an exploration of BIM–WLC application, identifying a difficulty associated with the integration of data that are heterogeneous. This study also points out that the estimation methods lack standardization and consistency. Altaf [18], in a similar study, identifies a challenge in terms of data exchange, which it proposes to solve using the IFC and COBie exchange formats. This author suggests developing databases that integrate WLC data. In [19], the author presents different comprehensive approaches to integrate WLC and life cycle assessment (LCA) into BIM. One can use existing BIM software for data extraction, but this method does not take advantage of all of the capabilities of BIM and can pose interoperability problems. Data are necessary to be exported to an external platform which will need to be developed, and the methodology will depend on the flexibility of the modeling software. Another approach consists of including the information in the BIM model, which in turn necessitates a long process for the construction of the model, requiring more human and monetary resources. The presented studies reveal a technological gap in the access, interoperability, and integration of project lifecycle data. One of the key aspects of a construction project is the volume and diversity of information involved [20]. Hence, in [21], Boje suggests that the information and data exchange format should evolve in maturity, moving from the plethora of data formats, in a context where information communication is based on sharing files which are partially related to each other, towards linked and open data technologies.

Linked data (LD) is a set of best practices relying on the world wide web consortium (W3C)-standardized technologies. LD presents a significant potential to improve construction projects and WLC integration in projects [22]. LD data can be used to represent connected knowledge models, thanks to the use of an ontology. Ontologies are the representation of knowledge, and the relationships within that knowledge, about a concept or object in a language that can be understood by machines [23]. The goal is to represent the fundamental structure of concepts and to provide all of the vocabulary necessary to build a shared knowledge base [24,25]. The concept of ontology has proven to be efficient for knowledge management and data integration between agents and systems. It ensures interoperability between agents and software and integrates a contextual reasoning facilitating information retrieval and the decision-making process [26]. However, compared with the increasing interest in PLM, not enough studies have explored the application of ontology for WLC. Thus, there is a need to propose WLC knowledge domain representation, considering new workflows offered by BIM and new technologies. The aim of this study is to propose a WLC ontology to provide an operational framework for this area of expertise. This ontology will allow WLC to be integrated as a shared field of knowledge, reflecting the life-cycle costs induced by processes or elements applied in a construction project. The paper provides major contribution for WLC, facilitating its integration with new technologies, such as BIM. It proposes an operational ontology, directly usable by professionals, which clarifies and standardizes vocabulary in accordance with international standards, notably ISO 15686-5 [12], thereby enhancing collaboration among stakeholders. The ontology also enables better decision-making based on reliable data by simplifying complex calculations. The knowledge represented in this ontology is reusable and adaptable across various projects and domains, allowing for flexibility in different construction scenarios while maintaining consistency and alignment with industry standards.

The introduction to this paper has outlined some of the issues faced by the technological integration of WLC and has positioned the research contribution. The following section will complete the literature review by exploring the concept of WLC as well as the application of ontologies in construction, and particularly for estimation practices. Section 3 will describe the design science research methodology used to build the ontology, together with the ontology construction methodology. Section 4 presents the results and describes the composition of the ontology. Section 5 will discuss the results, and the conclusions of the research will be in the final section.

2. Literature Review

2.1. Whole Life Costing

WLC enables capital expenditure and future expenditure to be estimated and controlled, making it possible to find the best trade-offs for optimizing the cost of a project throughout its entire life cycle [11]. The approach can be used to evaluate projects, forecast the performance of new technologies, allocate resources on important items, or conduct negotiations [13,27]. As specified in ISO 15686-5, the role of the WLC is to quantify life-cycle costs to feed decision-making and evaluation processes. WLC analysis can be carried out at any phase of a project, but it is in the preliminary phases that it will most influence future costs and generate value [27]. In most cases, in the public sector, the approach is driven by policies and, in the private sector, by customer demands. Unless it is formalized in a contractual agreement, this approach will almost never be voluntary [28]. WLC practice is limited by short-term savings behaviors. This approach to investment can distort the economic performance of a project, as it favors the return on investment (ROI) indicator, which is easily increased by reducing initial expenditure [29,30]. This practice leads to a lack of motivation and causes a lack of knowledge and awareness of the WLC benefits, making it little used. Additionally, a lack of methodology reinforces its complexity [13,29,31].

Today, this problem is partly covered by the various standards that have emerged on the subject. These standards provide guidelines but appear to be rather static in defining costs and parameters when compared with construction projects, which all have their own unique specificities. Thus, traditional methods are used to prevent future over-expenditures, like adding a budget margin [32]. Another complexity of WLC is data collection and management. Calculating WLC requires a large amount of data over the entire life cycle and is dependent on the availability of such data [13]. There is still a methodological gap in the collection of these data, as there are only a few or no systematic collection approaches and suitable databases for collating them [30]. This activity can therefore be very time-consuming for the estimator [27]. Historical data must be reported on a basis comparable to the context of the new project, which can sometimes be difficult [33]. Building operation and maintenance data, as well as data on the life cycle of materials and equipment, are sometimes difficult to obtain. Thus, the final obstacle identified for WLC is its high degree of subjectivity [13,28,31]. This subjectivity implies a risk of over- or underestimating the WLC of the project [34], though the involvement of the human factor increases the risks resulting from estimation [35]. Thus, the inherent challenge of WLC is to make the right assumptions, as early in the project as possible, when little information is known [32]. Missing or inaccessible data can also reduce confidence in the calculation, which requires predictions. Indeed, in [32], Pearce points out that stakeholders favor alternatives whose behavior they know, rather than those for which little information is available and whose behavior is difficult to predict. The key to reliable WLC is to build models that require the least possible input data based on assumptions on the part of the estimator [31].

2.2. Ontologies for Construction Projects

W3C establishes standards and guidelines to enable the creation of a web that prioritizes accessibility, internationalization, privacy, and security [20]. The concept of linked data presents a set of good practices to reach this vision, as follows [20]:

- Unique Resource Identifier (URI): These specify a resource identifier, commonly in the form of URLs.
- Extensible Markup Language (XML): A markup language used for describing and structuring file content and as a syntax format.
- Resource Description Framework (RDF): A data model that uses triples to form statements and can be serialized in formats like RDF/XML, Turtle, or JSON-LD. RDF datasets are stored in specialized databases known as triple stores.
- Resource Description Framework Schema (RDFS): An extension of RDF introducing an extra layer of semantics, providing a vocabulary for structuring these triples by defining classes, properties, hierarchical relationships, and constraints.
- Web Ontology Language (OWL): Extends RDFS with logic-based constraints, enabling automatic reasoning.
- Simple Protocol and RDF Query Language (SPARQL): A query language for managing RDF data in a standardized way.
- RIF/SWRL: Rule languages for defining relationships between concepts in an IF-THEN format.

Ontology appears as a way to give meaning and structure to linked data by leveraging standards like RDF, OWL, and SPARQL. It enables the organization of knowledge and facilitates the management of data. Over the past few years, the construction industry has begun to benefit greatly from the development of ontologies. As the adoption of ontologies increases, researchers and institutions have sought to structure and align domain-specific ontologies with standardized frameworks. The Centre for Digital Built Britain (CDBB) has analyzed top-level ontologies and industry data models to clarify their role in digitalizing construction processes [36]. With the development of BIM in particular, research has shown the significant potential of the use of the semantic web and linked data and has revealed the need for solutions to multidisciplinary data connection [37]. Indeed, "classic" web exchange services are subject to interoperability due to data from various sources and workflow automation is limited as data content is mostly human reading only [38,39]. In a construction project, the same element can take on distinct characteristics depending on the context in which it is used [39]. The process to make contextualized data available is semantic data integration, which adopts a conceptual representation of data and their relationships [40]. In [39], the study reviewed the application of the semantic web in construction. The authors suggest that good data integration would help current computer systems, which struggle to describe contextual differences between elements, to better process input information data. The same authors also argue that the use of the semantic web facilitates the bidding process and improves the information management from multimedia data, even if unstructured. To this purpose, Mercier, in [41], has concluded that ontology is a comprehensive tool to unify heterogenous data from various sources. Ontologies serves as a foundation to collect, edit and share data, which in the certain context of an ontology domain, reflect a certain knowledge domain, naming a knowledge base [38]. A knowledge base capturing multiple information through multiple data collections, thanks to ontologies, can be considered as knowledge repositories for project agents (humans and machines), which can be efficiently accessed to provide decisions [39].

Several ontologies for describing the construction context have been proposed [22]. Among these, the building typology ontology (BOT) and the digital construction ontology (DiCON) appear to currently be the main references to describe buildings. BOT ontology provides a simple and extensible structure to describe objects in the context of a building, addressing the needs of stakeholders throughout its life cycle [42]. The DiCon aims to facilitate the representation of digital construction processes, defining terms related to built assets, building design, construction project planning, and construction planning [43]. An IFC ontology, ifcOWL has also been proposed to ensure proper use of BIM models with ontologies [44]. The ifcOWL ontology enables the representation of building data using the semantic web and linked data technologies. By converting IFC data into RDF graphs, this approach allows for easy linking with other datasets. This interconnectivity facilitates better integration of data flows, thereby improving efficiency and collaboration among stakeholders in construction projects. Thus, the pathway to develop specific ontology applications is open, consistent with the adoption of BIM currently under implementation in the construction industry.

2.3. Ontologies for Construction Estimating Practices

The use of ontologies in construction cost estimation relies mainly on their integration of multiple data sources and on their ability to structure complex information and automate decision-making processes. In Ma's study, construction cost estimation specifications are modeled through ontologies to automate tasks such as item discrimination and quantity calculation [45]. This approach makes it possible to standardize data from multiple sources, reduce human error, and optimize the accuracy of estimates. Other work, such as in [46], demonstrate the integration of ontologies within the framework of BIM models, where information relating to construction conditions, work items, and estimating concepts are interconnected via reasoning rules. This method enables BIM data to be exploited more efficiently, notably by converting models into machine-readable data via RDF formats. These sub models facilitate the extraction and management of data from a variety of sources such as construction specifications, documents, or CAD drawings, offering a more holistic view of costs. Ontology-based cost estimating software can integrate measurement standards such as new rules of measurement (NRM), enabling uniformity of calculations and better integration of BIM tools [47]. This allows data to be standardized and structured, providing a common basis for the various parties involved in a project. In [48], Staub-French proposes an ontology based on design functionalities that directly influence construction costs. The ontology enables estimators to customize the identification of design conditions and automatically generate feature-based models rather than relying solely on designer-driven product models.

Very few ontologies for WLC are available (See Table 1). In [49], Gao proposed an ontology for coupling WLC and machine learning. The proposed ontology aims to collect data generated from building systems through the ontology to feed a machine learning algorithm for WLC facilities analysis. This effective approach is essential to optimize facility management, but the ontology is focused on the data integration of WLC into the machine learning model, without describing the WLC methodology. Instead, it focuses on structuring data sources and tools for analyzing WLC via machine learning. In [50], Zhang proposes an ontology to assist structural engineers in making design decisions by considering sustainability, safety, and cost. The ontology organizes the related knowledge to automatically generate calculations on the impact of material choices in terms of CO_2 emissions and costs. This study allows a WLC estimate based on materials price but does not represent the full domain of WLC knowledge, limiting its use for the specific purpose of this study to propose a semantic representation of it. Ref. [51] models life cycle sustainability assessment (LCSA). The ontology allows the conversion of open-access databases like EXIOBASE into machine-readable formats, facilitating querying via SPARQL requests. WLC is not explicitly mentioned as a distinct domain in this ontology, but cost elements are included in the flow class, which contains the measurements of entities produced or consumed in an activity. Thus, it enables the capturing of life cycle costs at specific times thanks to the OWLTime ontology. Finally, the most comprehensive ontology and WLC solution is that proposed by El Diraby [52,53]. This author's ontology, focusing on LCC (not WLC), provides a web-service LCC solution based on the ontology representation of LCC costs and cost factors influencing their values. The OWL representation of LCC costs and cost factors allows for a link between both, facilitating the automation of risk analysis and the understanding of cost implications. Furthermore, the whole proposed system is based on knowledge management, using a lessons-learned database which can be useful for data mining. Since the consistent knowledge-based approach from the author El Diraby in 2005 and 2006, which at the time of this paper represents a gap of 20 years, no other study has considered such work or improvement considering WLC in construction. Thus, a clear gap appears concerning WLC knowledge domain representation for the actual construction industry context.

Indeed, there is a need to consider new workflows offered by BIM and new technologies and bridge the gap of data integration. With consideration of the work proposed by El Diraby, this paper aims to propose work to improve WLC knowledge area representation in the construction industry by proposing a novel WLC core ontology. In [53], the author identifies as future work the integration of data mining, data patterns analysis and fault tree/risk analysis, as well as the functionalities of decision maker profile analysis and online price negotiation. A core ontology would help give a flexible framework to pave the way towards this suggested work. Finally, while the ontology proposed by El Diraby is considered for a large company, this paper is aimed at building experts seeking to integrate WLC in their processes. In addition, this study will use ISO 15686-5 as a basis upon which to improve the standardization of the ontology.

Table 1. Overview of WLC-related existing ontologies.

Ontology	Key Features	Benefits	Challenges	Integration with BIM Practices	References
LCCA-ONTO	Aggregating data from existing buildings to feed a machine learning algorithm	WLC estimation at the early design stage; supports FM decision-making	The ontology focuses on data aggregation and does not represent the WLC knowledge domain	Uses BIM as an ontology class to extract building systems data	[49]
Ontology approach for structural design considering safety, environmental impact and cost	Assists design choices with safety, cost, and environmental criteria; material-based cost and impact reasoning	Enables multi-criteria assessment at the design phase and the automation of CO_2 and cost calculations	Covers material choice only, lacks holistic WLC structure	Not implemented; the authors mention BIM integration as future work to automate data acquisition and enhance decision-making	[50]
BONSAI ontology	Generic LCSA support; uses EXIOBASE and OWLTime; captures flows and impacts	Cross-domain queries and data interoperability	WLC is not the core focus, the cost is modeled only in flows	No direct integration; data from LCA databases	[51]
LCC Core model	OWL-based LCC schema; integrates costs and influencing factors; ser-vice-based architecture.	Supports decision-making; structured Knowledge Map approach	Focus on LCC only; needs update to current tech/BIM	Not mentioned; No link to BIM or models	[52,53]

3. Methodology

This research aims to propose a novel WLC core ontology. This work was conducted through the design science research (DSR). DSR is a methodology aiming at generating new knowledge and artifacts that will answer practical problems [54]. The foundational problem identified is the underutilization of the WLC approach in building projects due to inefficient heterogenous information integration. Using abductive reasoning to propose an artifact, as suggested by Dresch, the study will propose an ontology to overcome the identified problem. As the artifact of this study will be an ontology, the methodology proposed [55], namely ontology-based design science research (ODSR), has been chosen to complement DSR. This method is a derivation of DSR that considers the development of ontology as a central artifact. ODSR is based on the well-known iterative framework of design, rigor, and relevance cycles [56]. The ODSR research framework of the present study is presented in Figure 1.

The first step involves is about understanding the study's environment and its knowledge base. The knowledge base is defined by exploring the literature, the applicable semantic web technologies and the retrieval of existing ontologies. To define the environment domain and ensure the methodology stays in an applied research approach, two surveys of estimators and economists from the "Association des Estimateurs et Économistes de la Construction du Québec" (AEÉCQ) were conducted. AEÉCQ is the professional body that brings together construction cost specialists in Quebec, working towards the recognition and best practices of the profession. As the literature review indicated, WLC is a practice that is typically not widely adopted. Therefore, the survey method was chosen to rapidly get an overview of the context. Both questionnaires were designed by the authors, ensuring their alignment with the professional context. The initial step was to comprehensively understand the current state of knowledge within the organization, representing most of the provincial financial engineers. This first investigation aimed to define the current state of WLC knowledge and practice among construction economists and estimators. Twenty-one respondents participated in the survey. The initial sample was low, which can be attributed to the low adoption of WLC and the limited interest in this approach. This first survey was administered online and consisted of the following questions:

- Have you ever witnessed or practiced the approach in a project?
- For what reason(s) have you not used the approach?
- In what context was the approach conducted?
- Do you think the approach has the potential to improve construction investments and the role of estimators in projects?
- What would you need to start using this approach?

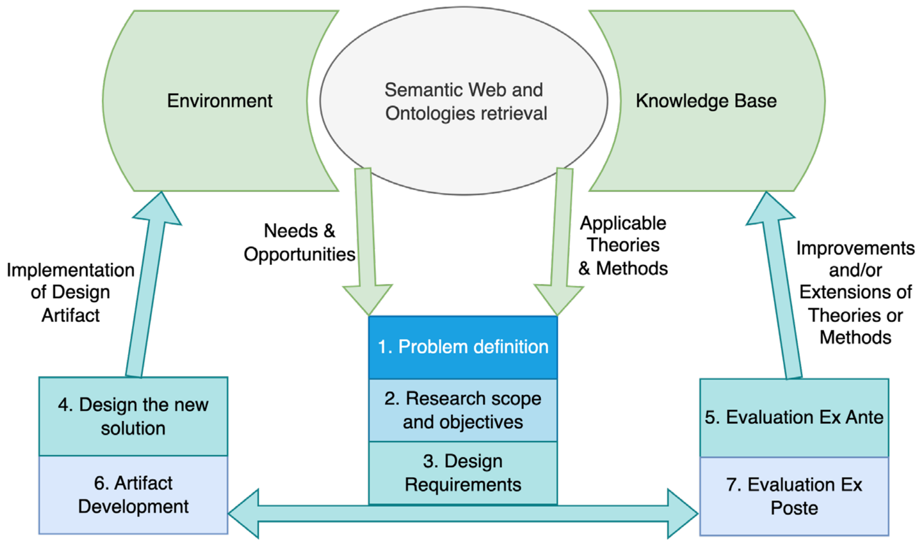

Figure 1. ODSR artifact development framework, adapted from [55].

With the understanding of the first results, a second survey was undertaken in order to understand how to take action considering the context of practices of the professionals. The second survey was a real-time survey, presented during a technical congress organized by the same organization. The survey aimed to confirm the tendencies of WLC with about 50 participants. A survey was conducted once more to ensure that the opinions of a set number of present financial experts were captured, as it was not feasible to engage in discussions with all attendees during the event. The sample was deemed sufficient given the number of respondents in the initial survey and its representation of a substantial proportion of the participants at the organization's congress. The following questions were presented:

- Do you think that adopting WLC is a logical next step in adopting new technologies?
- Would you be ready to use the approach in the near future?
- Rank the most pressing challenges you face in integrating WLC into your practices.
- Do you feel the information needed for WLC is currently too fragmented between different systems and stakeholders?

This step allows one to define the needs and opportunities of the studied domain and review the applicable theoretical background and methods applicable in the study context. Both surveys were conducted anonymously and focused solely on factual information, excluding the collection of confidential or sensitive data. Additionally, both surveys were distributed with the consent of the AEÉCQ and its members.

Step 1: With the established context of the research, the first step is the problem definition, where a research question must be formalized as outcome [54].
Step 2: The second step will define the scope and objectives of the research, which will also define those of the ontology to be constructed.
Step 3: The third step can then be undertaken by setting the design requirements. To ensure consistency, a focus group has been organized to fill this template. A group of five economists and estimators with experience in WLC were regrouped to reflect on a WLC ontology-based solution to define the correct ontology specifications. The focus group was selected to facilitate debate among estimators regarding their practices and to propose a consensus-based solution. This approach aims to mitigate researcher bias in interpreting the testimonials of estimators. Each participant agreed and signed an information and consent form from the Ethical Research Committee of the École de Technologie Supérieure.

To complete this methodology, a method to construct the ontology also had to be chosen. The present work used the NeON method [57]. The choice was made due to the flexibility of the method, allowing for the proposal of multiple approaches based on different data sources. The NeON provide a complete guide for ontology construction, assisting the user from the first phases of reflection. The NeON methodology proposes nine scenarios, as follows:

1. Create the ontology from scratch
2. Reuse and reengineer non ontological resources
3. Reuse ontological resources
4. Reuse and reengineer ontological resources
5. Reuse and combine ontological resources
6. Reuse, combine and reengineer ontological resources
7. Reuse ontological schemes
8. Ontology restructuring
9. Localize ontological resources

Considering the existing ontology, scenario 4, “Reuse and re-engineer ontological resources” was chosen. This ontology engineering method will take place in the third step of the research framework by developing the ontology design specifications (ODS).

Step 4: The fourth step will be the design of the new solution. This phase involves analyzing the ISO 15686-5 standard to convert it into an ontology. Additionally, it encompasses the creation of the ontology to facilitate a preliminary evaluation in the subsequent step.
Step 5: The fifth step aims to evaluate the ontology in a first ex ante evaluation to ensure its implementation in the environment and knowledge base. This will lead to another cycle of design where steps 1 to 3 will be reviewed.
Step 6: The final step leads to the final artifact development. ODSR suggests a thorough evaluation by mapping the ontology to existing ones to validate the results and be able to communicate the findings.

4. Results

4.1. Environment and Knowledge Base Definition

The WLC knowledge base was presented through the literature review in the previous part. In this section, the environment of the application domain is explored.

The results of the first survey, presented in Table 2, show that 76% have never applied the approach to their projects and half of them had never heard of the approach. The most selected answers to the question about why the WLC was not used are “lack of time” and "lack of knowledge". These responses are closely followed by the lack of demand and lack of tools to realize the WLC, while, among the "other" responses, the three respondents specified, "never had to use it", "contractual barriers", and "not applicable". The third question shows that, in most cases, it is the client who is the main requester of the approach. In the "other" responses, one outcome indicated that the approach was carried out as part of a design–build–finance–maintain mandate and another as part of an economic evaluation. Question 4 informs that most estimators (76%) think that the approach could improve their role and project investments. Finally, the main needs felt by estimators and economists are the need for training (33%) and customer demand (31%). There is also a need for software and databases (13%). The other responses (10%) were from participants stating the need for a "Modification of the contractual approach" and "Involving all parties at a very early stage".

Table 2. Survey 1—Online questionnaire.

Question	Response	Percentage
Have you ever witnessed or practiced the approach in a project? N = 21	Analysis leader	10%
	Witness	48%
	Analysis interpreter	5%
	Never heard of it	38%
For what reason(s) have you not used the approach? N = 20	Lack of Time	26%
	Lack of knowledge	26%
	Lack of skills	5%
	Lack of tools	16%
	Not requested	21%
	Others	16%
In what context was the approach carried out? N = 13	Customer request	60%
	Certification	7%
	Estimator proposal	20%
	Others	13%
Do you think the adoption of WLC will improve investments practices and estimators' role in construction projects N = 21	Yes	76%
	No	5%
	I do not know	19%
What would you need to start using WLC? N = 20	Training	33%
	Software	13%
	Data base	13%
	Customer requests	31%
	Others	10%

The results of the second survey are presented in Table 3. Among the 50 professionals questioned, 94% seem aware of the importance of WLC considering the construction sector technological improvement, and 88% seem ready to engage in the adoption of this approach in the coming years. In question 3, 34% ranked in first position the need for reliable data and a common understanding of WLC. The following needs are the process definition ranked first by 14% of respondents, and integration with existing tools and integration of fragmented data, both ranked first by 10% of the attendees. Finally, 86% of professionals believe the information is too fragmented to easily lead to WLC analysis.

4.2. Problem Definition

The surveys reveal a strong interest in WLC but also a significant under-utilization of the approach in projects. Respondents put forward the challenges of lack of time, knowledge, and requests. This is reflected in the need for a common understanding of WLC and for reliable data which can be painful to get. The results also underline a need for tools and resources to facilitate the adoption of the approach. Although the professionals said they are ready to use WLC and hope for an improvement of their practices, the results demonstrate that they still need to be supported in their knowledge acquisition. These findings serve to confirm the need for an operational framework structuring WLC knowledge and facilitating its integration into digital tools and processes. Thus, the following research question guides this study: How can a core ontology be designed to structure and integrate WLC knowledge in construction projects to support its adoption and digital implementation?

Table 3. Survey 2 results—Real-time questionnaire.

Question	Response	Percentage
Do you think adopting WLC is a logical step in adopting new technologies? N = 50	Yes	94%
	No	6%
Would you be ready to use this approach in the near future (within 5 years)? N = 50	Yes	88%
	No	12%
Rank the most pressing challenges you face integrating WLC into your practices (Number of times an option is ranked first) N = 50	Reliable data	17–34%
	Common understanding of WLC	17–34%
	Process definition	6–22%
	Integration into the project delivery strategy	4–14%
	Integration with existing tools	3–10%
	Integration of fragmented data	3–10%
Do you feel that the information needed is currently too fragmented between systems and stakeholders? N = 50	Yes	86%
	No	14%

The results also help to position the concept of ontology. The absence of a shared understanding and reliable terminology justified the adoption of ISO 15686-5 as a semantic foundation, providing standardized definitions for lifecycle cost terms. The issue of fragmented data supports the design of a core and flexible structure, one that can be expanded and which promotes semantic interoperability across existing tools and heterogeneous data sources. The ontology approach developed through this research aims to fill these gaps by providing a standardized data structure and integrating WLC knowledge accessible to users. In addition, this ontology will be designed to efficiently coordinate with existing software and databases, thus meeting the needs for software tools. Considering that customer demand is a key driver of WLC adoption, the ontology should include performance indicators demonstrating WLC impacts on construction investments. Furthermore, the survey findings directly informed the ontology's design. The identified barriers were translated into competency questions (Table 3) and corresponding ontology classes and properties.

4.3. Design Requirements

Ontology Specification

The NeON methodology's ontology specification document (OSD) template has been used to define the ontology specifications. This document provides guidance to define the scope, requirements, vocabulary, and modeling language for the ontology development. To ensure consistency, a focus group has been organized to fill this template. A group of five economists and estimators with experience in WLC were regrouped to reflect on a WLC-ontology based solution to define the right ontology specifications. The OSD template is presented in Table 4.

Table 4. Ontology specification document.

	Specification for the Ontology
Objective of the ontology:	In accordance with the ISO15686-5 standard, the objective of the ontology is to quantify the lifecycle costs to improve decision-making and evaluations in projects.
Scope	The ontology will have to be applicable to any construction project. The ontology will have to be high level, representing all life cycle phases but allowing any user to use its own estimation methods, scope of costs, parameters, and processes.
Implementation language	The ontology will be implemented with the OWL language.
Users	Users of the ontology will be estimators, economists, environmental analysts, architects, and owners.
Ontology uses	The ontology will be used to provide information about the WLC of a project, to learn about the costs at specific phases of a project, to learn about the financial impacts of the choices made.
Ontology requirements	Non-functional requirements: The ontology must be based on existing norms (ISO 15686-5, ISO 19650) and be flexible. Functional requirements (competency questions (CQs)) and their answers, as follows: - What is the WLC cost of the project? The WLC cost is the sum of “all significant and relevant initial and future costs and benefits of an asset, throughout its life cycle, while fulfilling the performance requirements” (ISO) - What are the cost components of the WLC of my project? The life cycle cost includes acquisition costs through to end-of-life, and whole life cost includes LCC plus non-construction costs, benefits, and externalities. - What is the WLC cash flow of the project? Relevant costs (and income and externalities if included in the agreed scope) arising from acquisition through operation to disposal. - What are the financial impacts of the elements and processes on the WLC of my project? Additional costs or cost savings compared with a baseline cost. - What are the expected costs at a specific time? Costs arising at the specific time of a project.
Pre-Glossary from CQs	Whole life cost—project—cash flow—financial impacts—elements—processes—time
Pre-Glossary from answers	Sum—initial costs—future costs—benefits—asset—life cycle—performance requirements—life cycle cost—acquisition costs—exploitation costs—maintenance costs—end of life costs—non-construction costs—benefits—externalities—additional costs—cost savings—baseline cost

4.4. Design of the New Solution

Ontology Development

As described by the NeON methodology, the first phase of the development is the ontology search, assessment, comparison, and selection. The literature review revealed that only the ontologies of Gao and El Diraby explicitly deal with the topic of WLC. Additionally, it reveals that only the ontology proposed by El Diraby explicitly presents the knowledge area of WLC while being unaligned with the ISO 15686-5. Considering the goal of the present ontology development process, the NeON scenario use will be “scenario 2: non ontological resource reuse” with the ISO standard as a basis. The ISO 15686-5 has the advantage of defining a standard glossary of terms for WLC in the construction industry, thus an ontology based on this standard should facilitate WLC adoption.

The given scenario of NeON starts with the initial activity, which consists of three main stages: data collection, which in this case consists of researching the ISO 15686-5 standard; conceptual abstraction, aiming at extracting the conceptual schemas of the resource; and finally, information exploration, aiming to understand the conceptual schemas and content of the resource. The conceptual schemas from the standard are presented in Figures 2 and 3 (Copied by Groupe de Recherche en Intégration et Développement Durable en Environnement Bâti with the permission of the Standards Council of Canada (SCC) on behalf of ISO. The standard can be purchased from the national ISO member in your country or the ISO Store. Copyright remains with ISO.).

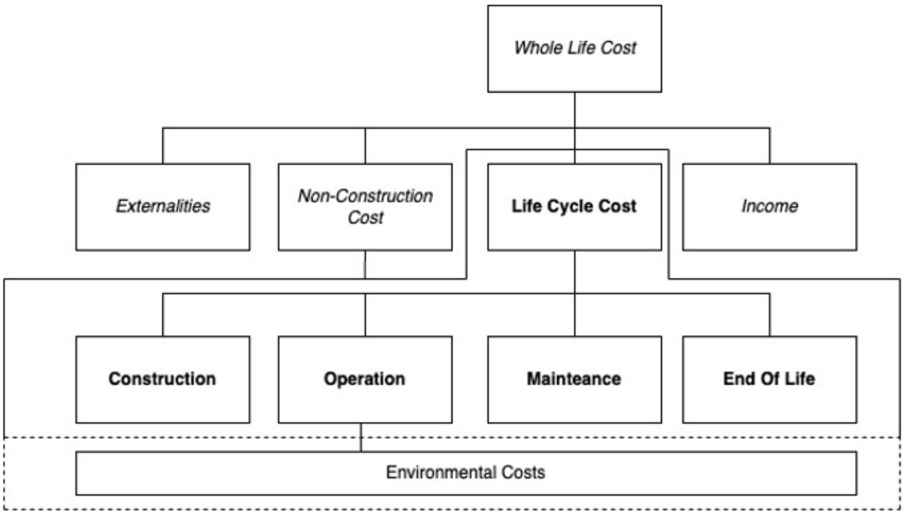

Figure 2. Conceptual schema adapted from [12].

Detail level	Steelwork, concrete, in situ or pre-cast, etc.	Cladding type, roofing type, glazing, JoInts, etc.	Electrical, mechanical, plumbing plant and equipment, lifts escalators, etc,	Paint types, celling tiles, floor coverings, door fittings, etc.	Considerations: Costs Functions Maintenance Environment Disposal Life Cycle Stages: Planning Construction Operation Maintenance End-of-life	**All levels**
System level	Foundations, solld or framed wall and floors	Cladding, rooting, windows and doors	Energy, ventilation, water capacity. communications etc.	Wall, floor and ceiling finishes		
Strategic level	Safety and durabilty	Location and external environment	Comfort and use	Maintainability and Internal environment		

Figure 3. Conceptual schema adapted from [12].

The standard presents, in Figure 3, the approach as a scalable arbitration method, enabling the impact of deferred costs to be better considered in investment choices. It demonstrates this scalability by detailing the elements to be taken into consideration at each phase of the project. The level of detail must correspond to the level of project phase. Data may be physical (e.g., building surface area), occupancy data (e.g., number of beds, occupancy hours) or related to performance and quality (e.g., appearance or operating expectations) [27]. For the costs to be considered, as Figure 2 shows, the standard differentiates between life cycle cost, which includes acquisition costs through to end-of-life, and whole life cost, which represents the LCC, plus non-construction costs, benefits, and externalities.

The next activity aims at the transformation of the resource into a conceptual model. In this phase, the conceptual schemas of the norm are translated into a model aiming at representing the WLC knowledge. The OSD helped to enrich the data model and adapt it to the needs expressed in the focus group. The model is shown in Figure 4.

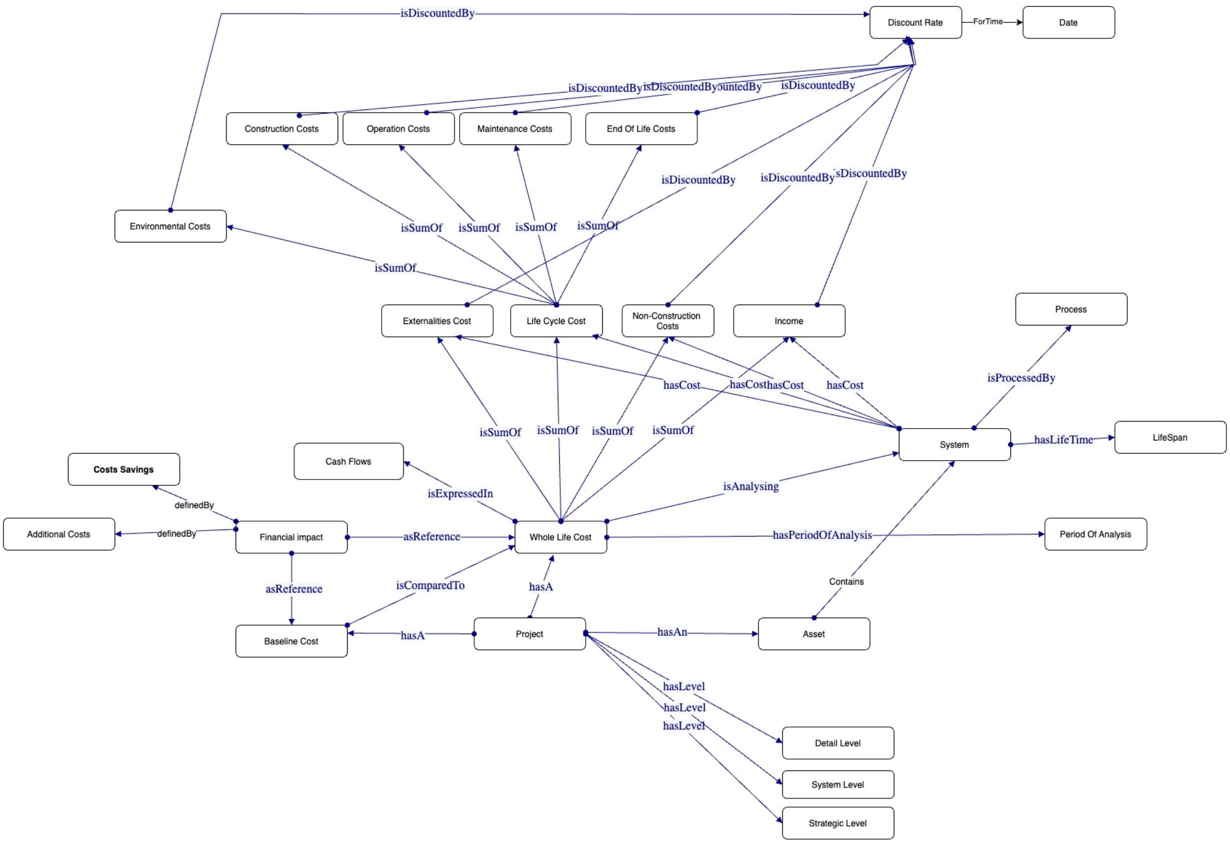

Figure 4. WLC consolidated conceptual model based on [12].

The conceptual model deduced from the ISO schema details the different cost components of the WLC, project phases and processes, the project settings necessary for WLC calculation and the relationship between them.

Finally, the third activity leads to the creation of an ontology based on the conceptual model. For this phase, the protégé software was used to create the ontology following the requirements previously defined. This phase encompasses the definition of classes, object properties, and data properties. The classes correspond to the concepts based on the vocabulary identified in the glossary of terms and the definitions proposed by the ISO 15686-5. The ontology is completed with the relationships between the classes, which are defined thanks to the object properties. The classes are characterized by data properties, defining the type of data corresponding to the class. For this work, the aim is to propose a core ontology that will enable any user to develop it or connect it to other ontologies according to their needs. Thus, only the concepts needed to calculate the WLC have been selected. The following classes, object properties and data properties included are presented respectively in Tables 5–7.

Table 5. WLCONTO class descriptions.

Category	Description
WholeLifeCost	The class that groups together all of the costs involved in the life cycle of a project or asset.
Costs	A class grouping all cost typologies, subdivided into sub-classes including ConstructionCosts, OperationCost, MaintenanceCosts, EndOfLifeCosts, ExternalitiesCosts and EnvironmentalCosts.
DiscountedCosts	A class encompassing discounted versions of each type of cost to incorporate the notion of the time value of money.
DiscountRate	A class to model the discount rates applied to the calculation of discounted costs.
Time and its sub-classes DateOfInstallation and EndOfLifeDate	Represent the time dimensions essential to the WLC calculation.
PeriodOfAnalysis and the sub-class LifeSpan	Specify the scope of duration analysis.

Table 6. WLCONTO object properties description.

Object Property	Domain	Domain	Range
isSumOf	Defines that certain classes are the sum of other classes.	WholeLifeCost	DiscountedCosts
hasCosts	Links an entity to a set of associated costs. Sub-properties have been defined to specify cost categories, including hasConstructionCosts, hasOperationCosts, hasMaintenanceCosts, hasEndOfLifeCosts.	Project (and its sub-classes Asset and Element)	Costs
hasDiscountRate	Associates a discount rate.	Date	DiscountRate
isDiscountedValueOf	Links a cost to its present value.	DiscountedCosts	Costs and its sub-classes
ForDate	Indicates the date of an event.	Costs	Time
hasStart, hasEnd	Specify the start and end of an event.	Project	DateOfInstallation and EndOfLifeDate
hasDuration	Indicates the estimated duration of the scope of analysis.	Project	PeriodOfAnalysis

Table 7. WLCONTO Data Property description.

Data Property	Description	Domain	Data Type
hasCostValue	Represents the monetary value of a cost.	Cost	xsd:decimal
hasDiscountedCostValue	Captures the present value of a cost after applying the discount rate.	DiscountedCosts	xsd:decimal
hasDenomination	Provides a description or name for an entity.	Project	xsd:string
hasTotalValue	Represents the total sum of costs for a given set.	WholeLifeCosts	xsd:decimal
hasRateValue	Specifies the value of a rate.	DiscountRate	xsd:decimal
hasDate	Associates a specific date with a cost or event.	Time	xsd:date (a standard data type for representing dates in format YYYY-MM-DD)

The ontology integrates the core concepts necessary for the calculation of WLC. Each cost instance is associated with a specific year through the ForDate property, and discount rate instances are similarly linked to their corresponding year. This temporal structure facilitates the application of discounted cash flow logic, conforming to the ISO 15686-5 standard calculation expressed in Equation (1):

$$Discounted\ Cost = \frac{Cn}{(1+d)^n} \tag{1}$$

Discounted values are aggregated within a WholeLifeCost instance using the hasTotalValue property. The ontology also includes a lifespan class, enabling components or processes to be associated with an anticipated duration of use. While recurrence is not computed within the ontology itself, lifespan values can be retrieved by an external process to simulate recurring costs, such as replacements, over the defined analysis period. Lifecycle phases are represented through the subclasses ConstructionCost, OperationCost, and EndOfLifeCost, supporting phase-based classification and aggregation. Although values are currently manually entered, their structured representation facilitates future automation or integration with external data sources. The definition of these elements into the software are presented in the Figure 5, and the schematic representation of the main concepts of the ontology is represented in Figure 6.

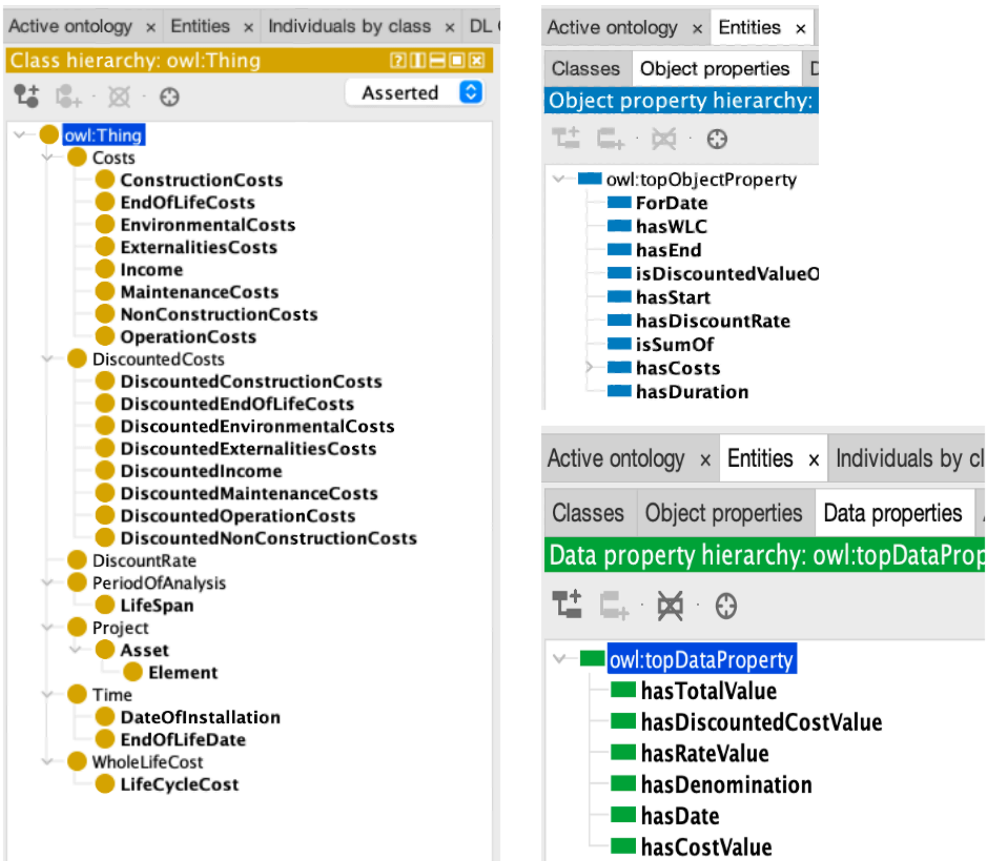

Figure 5. Classes, object properties and data properties in the Protégé software 5.6.5.

4.5. Ontology Ex Ante Evaluation

The ontology will be assessed according to the following four criteria: domain coverage, quality of modeling, application suitability and adoption and use [58]. Domain coverage assesses whether the ontology adequately represents the intended domain. This involves comparing the ontology with standard, user-defined term sets or representative data. In this work, basing the ontology on the terms and definitions of ISO 15686-5 ensures that the WLC domain is appropriately covered.

Modeling quality examines adherence to best practices, and assesses the ontology's syntactic, structural and semantic consistency. This involves using reasoning tools to identify logical inconsistencies and syntax errors. The reasoner HermiT 1.4 was used to check the ontology and returned a validation message confirming its coherence and consistency (Figure 7).

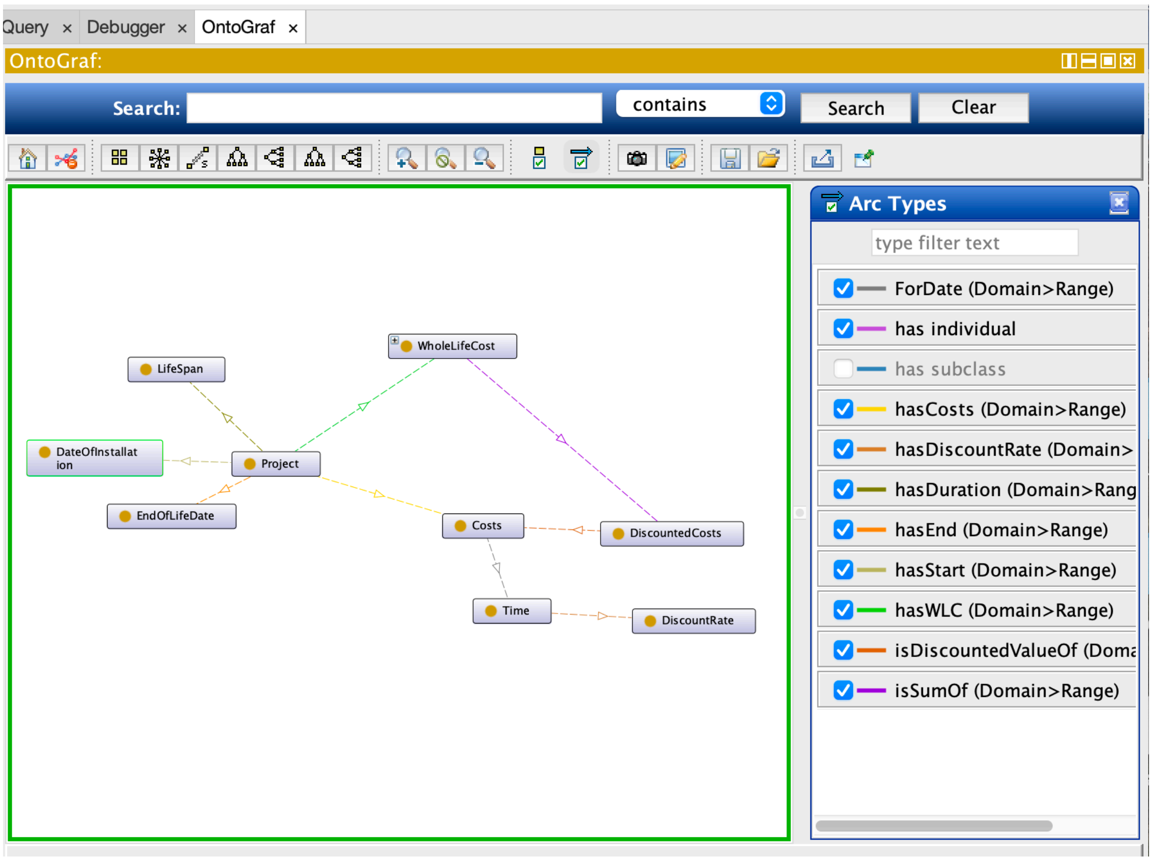

Figure 6. Schematic representation of the ontology from the ontology Protégé software 5.6.5.

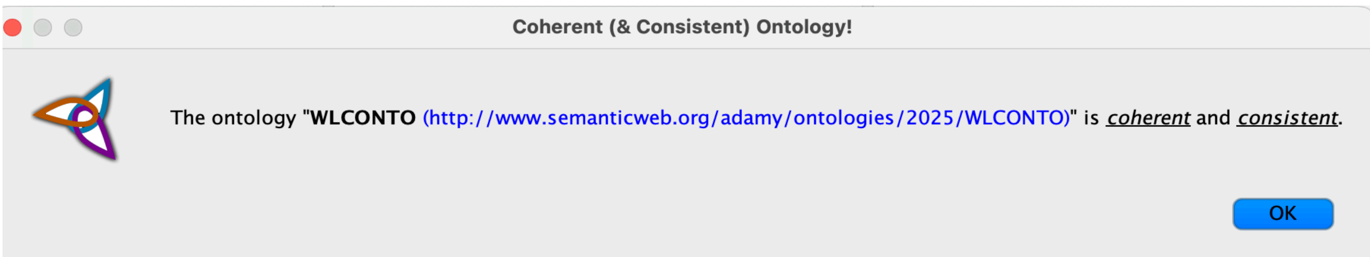

Figure 7. Message validation from the HermiT reasoner.

Application suitability determines whether the ontology is adapted to a specific use case by analyzing its performance and the relevance of the results generated in this context. In the present context, this means assessing whether the ontology can meet the requirements defined earlier, i.e., calculate a WLC. This requires creating instances, which are concrete examples of the ontology's concepts (e.g., a construction cost of 50,000 USD). These instances allow one to test the ontology's logic and ensure that the calculations produce accurate and expected results, validating both its structure and practical utility. At first, semantic query-enhanced web rule language (SQWRL) was used to query and display key data. SQWRL is a query language for OWL ontologies, enabling the extraction and reasoning over semantic data. The queries focused on extracting costs, their associated years of occurrence, and the corresponding discount rates. This method demonstrated the ontology's capability to represent lifecycle cost information in a structured and queryable format, ensuring its relevance for practical cost analysis applications (Figure 8).

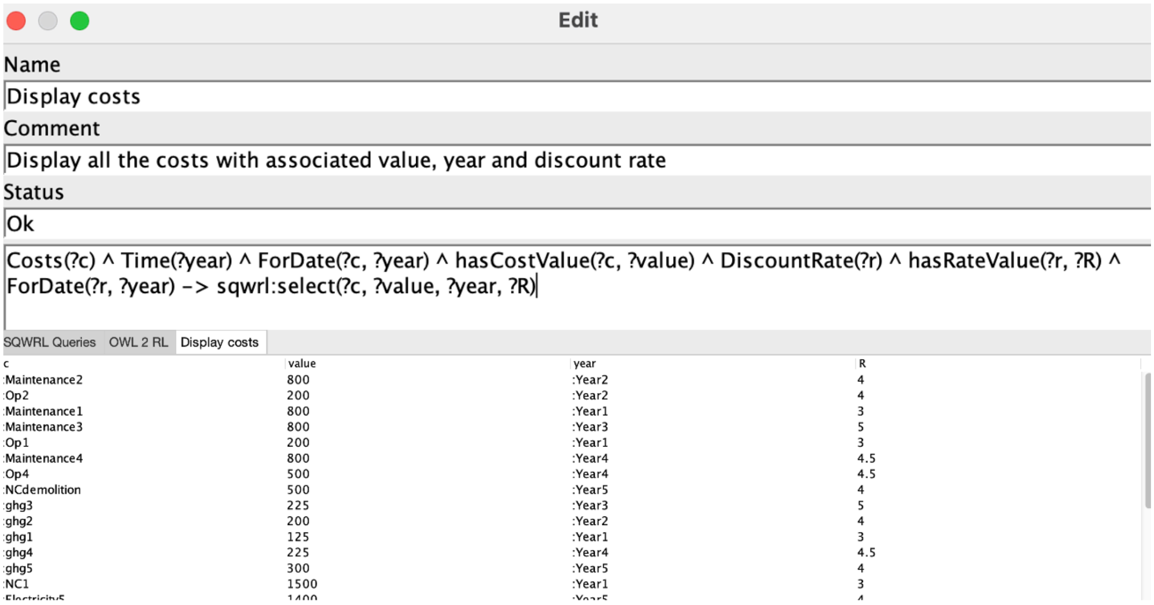

Figure 8. SQWRL results.

While SQWRL demonstrates the ontology's ability to represent lifecycle cost information in a structured format, it is limited in performing complex calculations, such as iterative operations or mathematical functions like discounting over time. Due to these limitations, Python and the Owlready2 library were used to implement a more robust calculation approach for WLC. Owlready2 is a Python library for working with OWL ontologies, enabling manipulation, querying, and reasoning directly within Python. By leveraging this tool, it was possible to calculate the discounted costs over time and assign the total value to the whole life cost (WLC) instance within the ontology. Below is the UML process to use the ontology to perform WLC calculations (Figure 9) and the results (Figure 10).

The process starts with the user creating input instances into the ontology. This step can be accomplished either through the Protégé software or by manually adding it directly in OWL language into the ontology file. Then, the Python 3.11.8 script loads the ontology and get the instances from the costs, DiscountRate, time and WLC classes for each cost's instances created. This step enables one to calculate the discounted costs and subsequently the WLC, which the script uses to update the ontology, allowing the user to visualize new data and results.

4.6. Artifact Development and Evaluation

Finally, the dimensions of adoption and use, measure how widely the ontology is reusable and can it be integrated into broader networks. This can be evaluated by analyzing its interconnections with other ontologies. The connection is tested with the BOT ontology, which is a widely adopted ontology in the construction domain, which provides a high-level and extensible framework for describing buildings, their components, and spatial relationships, serving as a foundation for integrating detailed domain-specific data [42]. The integration with BOT was performed by ensuring semantic consistency between the two ontologies through the alignment of classes, properties, and relationships. BOT's core classes are presented in Figure 11.

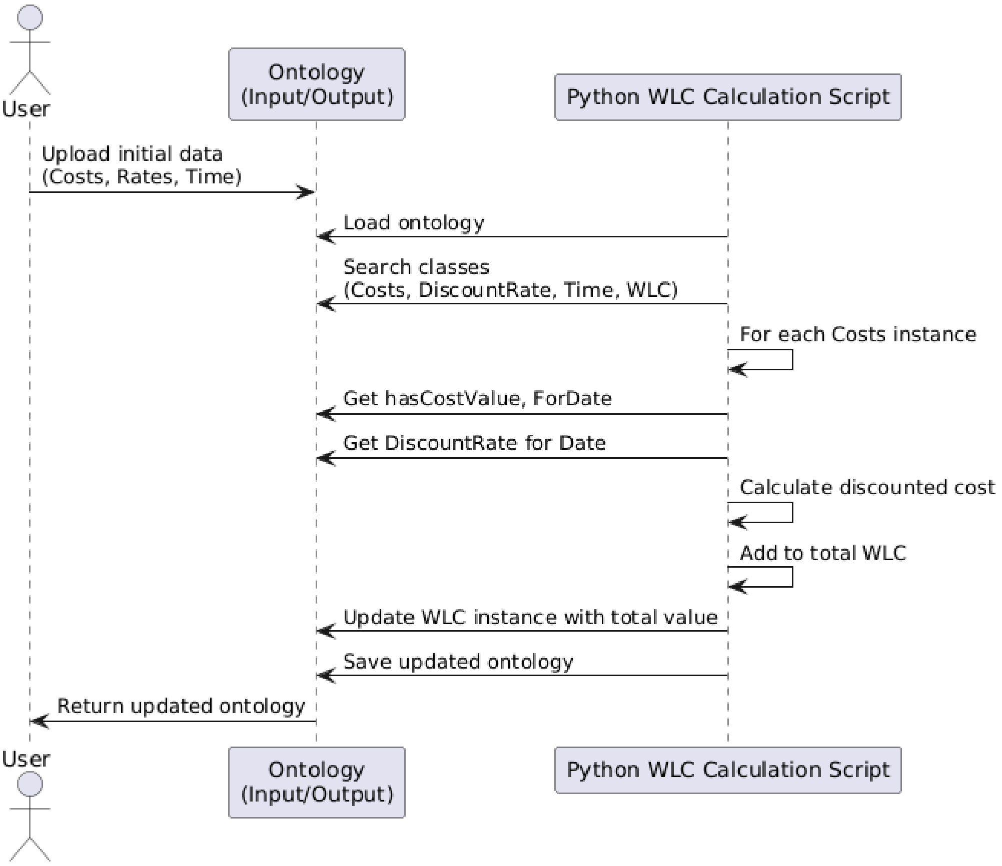

Figure 9. Python script for WLC calculation into the ontology.

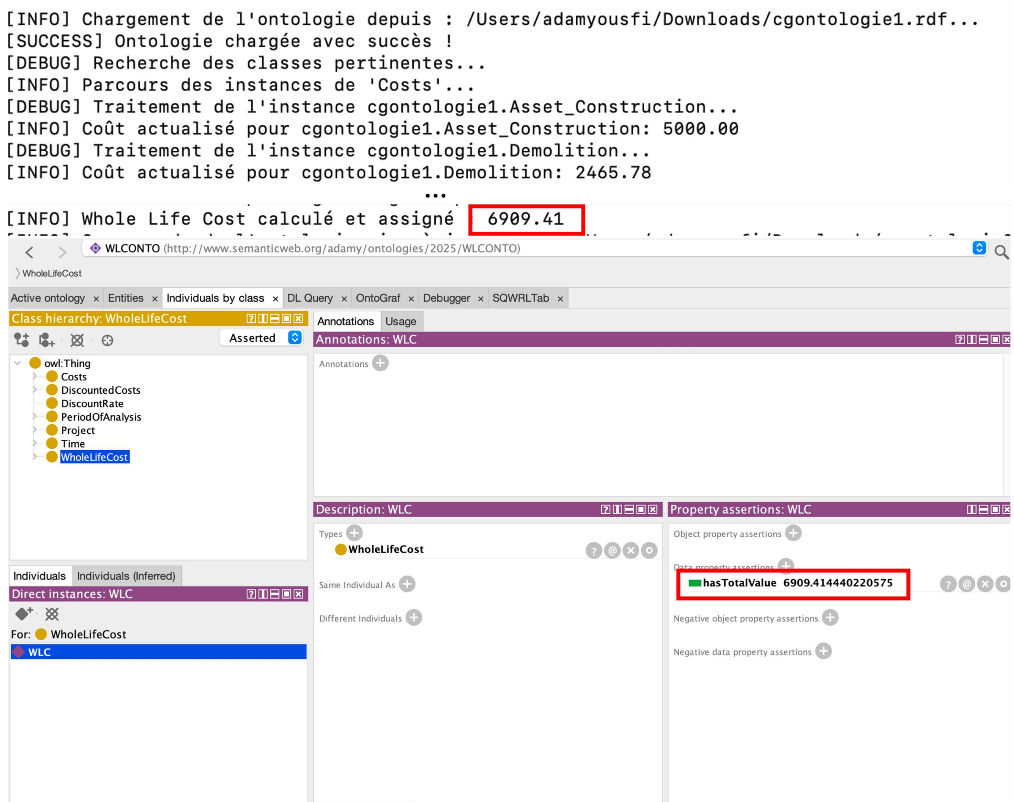

Figure 10. WLC calculation and integration of the result into the ontology.

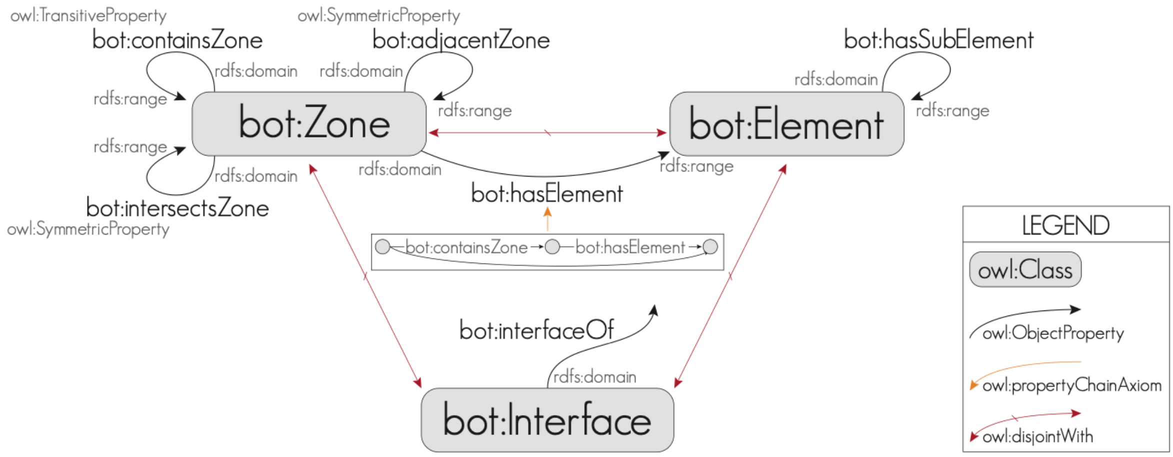

Figure 11. BOT structure.

Figure 12 demonstrates the results of this integration, where the previous SQRWL rule was tested to test the logical consistency of the BOT-extended ontology. The results confirm that the ontology can provide costs, their discounted value and associated year even for the added classes from BOT.

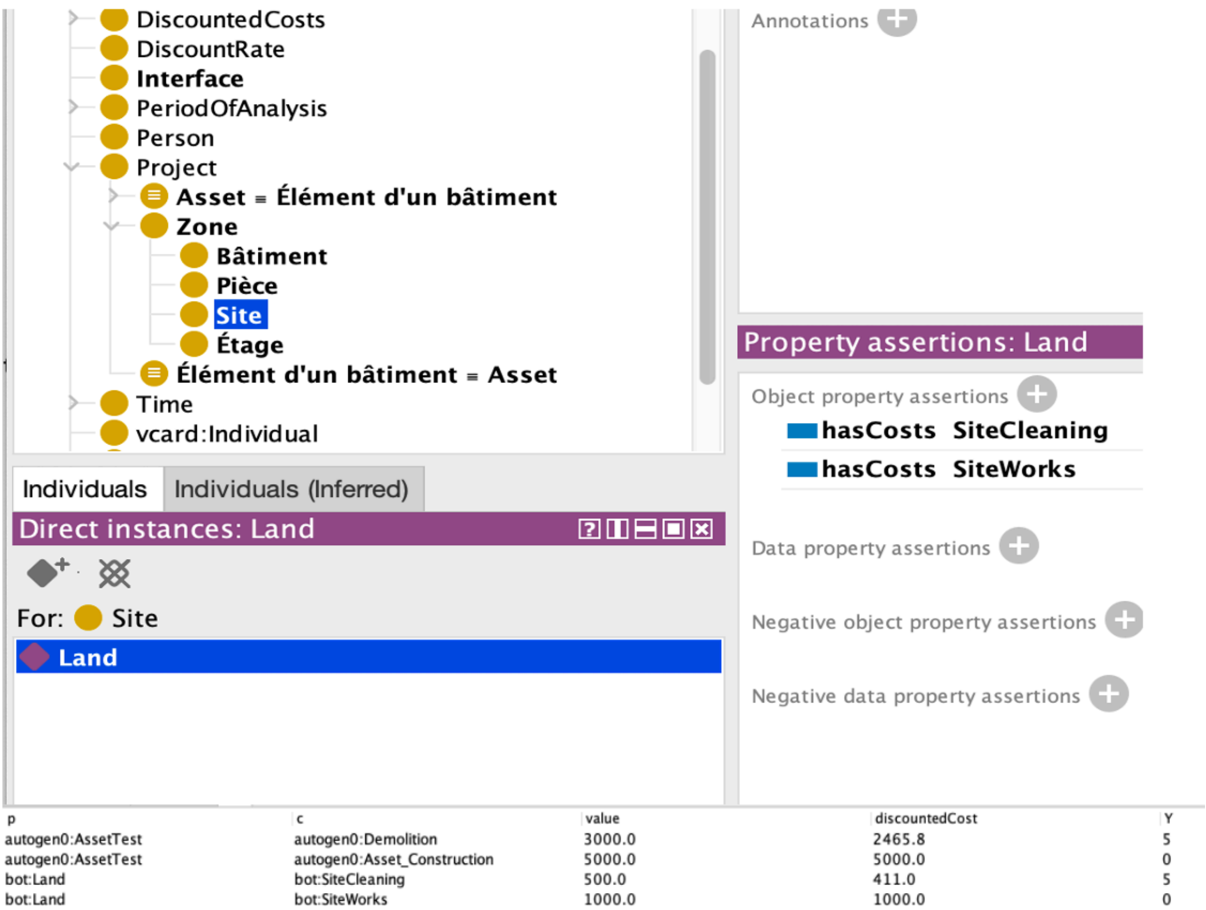

Figure 12. Ontology alignment with the BOT ontology. The figure shows the individual "Land" classified under Site (Zone). Translation: Élément d'un bâtiment = Building element; Bâtiment = Building; Pièce = Room; Étage = Floor; Site = Site; Zone = Zone.

To validate this integration, the python code was also tested, proofing the extensibility and usability of the ontology with other ontologies. The script adds the calculated WLC and new instances for the discounted costs into the ontology (Figure 13).

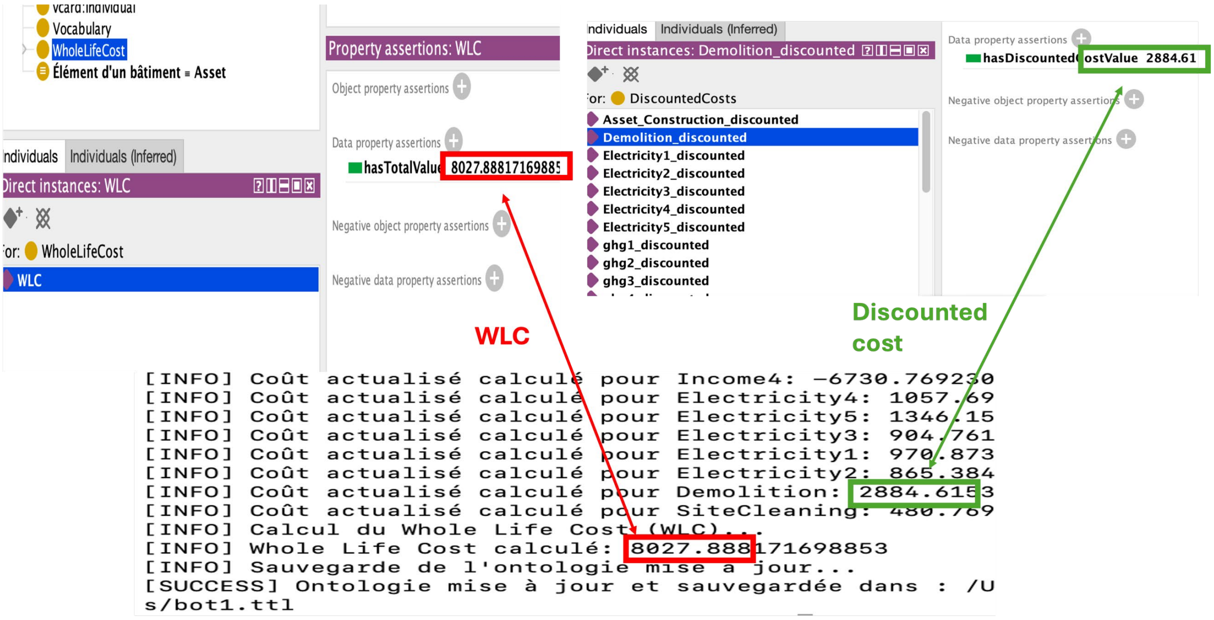

Figure 13. Integration of WLC results in the extended ontology.

The ontology was created to structure and standardize WLC domains in accordance with the ISO 15686-5. A conceptual model was created and mapped in OWL by using the Protégé tool. The ontology integrates cost categories, parameters, and temporal aspects required for WLC analysis. The validation confirmed the consistency and the compatibility of the artifact with other ontology standards. A Python script with the Owlready2 library was used to perform the WLC calculation for practical application. Although the ontology does not embed BIM structures directly, it is designed for semantic extensibility. In this research, the example of BOT ontology integration is used as a proof of concept to demonstrate that connections with existing BIM models are feasible. The result provides an ontological framework for the application and adoption of WLC in construction projects.

5. Discussion

The present research aims to improve how WLC is used in the construction industry by proposing a novel WLC core ontology. The result is an ontology aligning with the industrial context supported by the ISO 15686-5 standard, providing a robust artifact for the industry but also the academic sector as well. The ontology requirement specification document (Table 3) leads to the formalization of what practitioners really expect from a WLC analysis through the competency questions defined. The insights behind these competencies questions reveal the need for professionals to be able to manipulate cost data rather than simply estimate them. The total value of a WLC result appears to be an indicator for economists and estimators that must be used with their costs details in order to be useful. These professionals are eager to bring more value to projects by bringing their expertise to designers, and by being more involved in the design process so as to have a real impact on the project. Their willingness is there, but today they have very few tools enabling them to act as such in projects, as shown by the survey results indicating a lack of tools with which to apply the WLC approach. In fact, WLC uses a large amount of heterogeneous data from a variety of sources and therefore requires collaboration between stakeholders to carry out this analysis successfully. New information technologies are beginning to address this problem, with supposedly collaborative tools that enable several stakeholders to work at the same time in the same virtual work environment. BIM tools are the best example of this, with models that can be federated or cloud platforms that can enable collaborative working.

However, BIM is slowly maturing, and the interaction of these data is still very heterogeneous. Indeed, some uses of BIM still need further development to be better integrated because they are too specific, as in the case of cost estimation. Estimating requires the estimator to have a good knowledge of the project and the location of the information, which may be scattered across numerous documents, plans or models. Moreover, many estimators and economists continue to work in isolation within spreadsheets, limiting their ability to automate and, above all, to take a holistic view of all project data. For an estimator or economist, it is very difficult to find the time to go through all of these systems to find the right data and analyze them to propose a WLC with recommendations for the project, while carrying out typical tasks in their allotted time.

To support them, new semantic tools are needed to link systems and facilitate data access. This ontology paves the way towards this goal by providing a common semantic foundation. Compared with traditional workflows or nascent BIM practices based on bills of quantities, spreadsheets, or manual calculations, the use of a WLC core ontology offers a more integrated and interoperable approach. The ontology allows WLC information to be semantically formalized and linked to BIM models. Rather than requiring estimators to manually consolidate fragmented data, this structure supports automated data extraction and classification. In practice, cost values, lifetimes, discount rates and time references can be assigned to individuals within the ontology. Although OWL alone does not support arithmetic operations, the ontology serves as a structured basis for semantic interpretation and reasoning. The ontology does not aim to solve the lack of data itself, since it is not a cost or material database, but addresses the accessibility and management of data. It provides a semantic framework by which to connect heterogeneous datasets to building elements in a structured and interoperable way. Cost information, material types, and lifetime values can be imported from external sources and mapped to ontology individuals. This linking mechanism reduces manual processing, enhances consistency, and allows for dynamic updates as data evolve, improving data governance throughout the WLC analysis. This semantic infrastructure can support BIM integration, enabling digital models to be enriched with WLC-related metadata. As a result, estimators and other professionals can interact and share project data in a more coherent and collaborative environment.

The use of this WLC core ontology will mainly benefit the knowledge graph (KG) area. As introduced at the beginning of the paper, KGs are powerful tools for knowledge management. Based on ontologies, KGs are ways to structure data according to a formal schema (i.e., ontology) that defines entities, their attributes, and the relationships between them, enabling semantic reasoning, interoperability, and advanced querying capabilities. As part of the limitations of this study, the ontology presented is simply the basis of an emerging work, one which does not yet meet all of the objectives found in the competency questions. As a prototype, this ontology can only be used to verify the logic of the modeled knowledge. Each datum must be entered manually, and complex calculations require an additional script. The real value of the final solution for professionals will therefore only become apparent when a tool with an interface unifying ontology, project documentation and analysis will be developed. In the meantime, the results of this ontology have the potential to evolve into a robust WLC analysis solution. As presented in the literature review, El Diraby, has proposed a similar artifact based on an ontology [52]. The ontology proposes a hierarchical cost structure comparable to that developed in the present paper, with a decomposition into cost elements and sub-elements, but it is not based on a specific standard. Additionally, the cost element constitutes the sole real common element between the two compared ontologies in terms of OWL modeling. The WLCONTO presented here modelized the parameters of the WLC and integrated a discounted version of the costs to ensure consideration of the time dimension in the approach. El-Diraby, on the other hand, added another dimension by explicitly modeling impact factors that influence these costs. Although El-Diraby does not present the time management aspect, the overall artifact integrates the impact factors as well as collaborative management through a web services-oriented architecture, allowing knowledge management through a java interface. The author's solution allows for the manipulation of the cost data attributed to the OWL concepts and for the registering of the results into a knowledge database. In fact, the approach of El-Diraby and the approach through a WLC core ontology aspired to in this paper share the same thought. Both use an ontology of costs which need extensional modules to analyze the WLC of a product. The difference relies on the fact that the present paper aims to propose a core ontology which will make it possible to specify an OWL tree structure of specific costs as El-diraby has done, but also to specify project parameters and temporal dimensions in an OWL language to facilitate automatic WLC analysis and integration of heterogeneous data sources. Another difference is the calculation of the WLC itself, where El-Diraby use a calculator service allowing for the leveraging of Monte Carlo or fuzzy simulation to assess the WLC. This reveals the main limit of the present ontology, which does not integrate a risk analysis. Nevertheless, this point is to be solved in retrieving an ontology like the one in [57], and to map it to the present ontology. El-Diraby also shed light on a major benefit of ontologies, with the knowledge database allowing a company to access the lessons learned from previous projects.

The present study integrates both calculation and learning aspects, using the Owlready2 Python library, giving the opportunity to modify and query the ontology. It also allows the user to create and manipulate instances, add relations between them, and use a reasoner to infer new knowledge. With this approach, the whole WLC domain of knowledge can become a KG. A KG is a promising tool for the WLC adoption, as WLC data can be sourced by different stakeholders and systems, like BIM tools, estimation software and databases, plans or specifications. Nevertheless, the weakness of KGs is that data must correspond exactly to the concepts of the ontology to be processed. This is the reason why the present ontology has been based on ISO 15686-5 to describe the WLC concepts, providing a widely use language for WLC users. Unfortunately, simply using a standard as a basis will not be sufficient to ensure the use of this ontology. Firstly, other standards on WLC exist in different countries, like the ASTM E917. This means differences between standards exist and that may create disagreement between building economist communities. Secondly, all projects are different in terms of documentation structure and information. Thus, work will always be necessary to identify where the data reside in order to link them to the ontology. Both of these issues form a significant barrier for KG development. Nevertheless, the first problem could be solved if the body of standards as a whole provided an ontology version of their standard. This could allow one to realize a mapping between them, the same way as was achieved for this study, defining the equivalences between the concepts. This approach would allow a user to use any ontology from any standard as long as its usual standard is connected to it.

The second problem paves the way for future studies, as it can be solved by artificial intelligence (AI) tools. Indeed, an AI model trained with multiple scenarios of different documents and vocabularies would allow one to facilitate data integration and propose a smooth process. Going further, the AI model could also analyze the results to build predictive models for WLC calculation and optimization. This could benefit the conception phase of projects, in which it would be possible to propose constructive choices according to a real-time WLC simulation based on the AI model. In the same way, future studies around the internet of things (IoT) could also benefit from the ontology. In fact, IoT devices use ontologies to link real world data and computer systems in real-time. This can be used to monitor the WLC of a building in real time through its whole life cycle and inform the building managers in terms of budget and planification. Concerning practical implications, companies will need to map their data exchange processes, identifying where the data are coming from and where they go. Only after this will professionals be able to digitalize their processes, facilitating comprehensive data integration. As demonstrated, ontologies can be linked between them, thus, multiple processes could be linked together, allowing companies to work more cohesively and project stakeholders to work more collaboratively. Providing a thorough process of data in a project would allow for better collaboration but also a more rigorous procedure, one in which each deliverable is mapped and associated to a person in charge. The next step of this study is the creation of a KG based on this core WLC ontology and test its applicability in real-world projects by digitalizing the process of a company and linking it to this KG.

6. Conclusions

The present research provides a WLC core ontology aimed at providing a foundational solution against data fragmentation, lack of standardization and interoperability in construction projects in order to facilitate the use of WLC. The literature review explored the concepts of WLC and ontologies defining their underpinnings and exposing the existing WLC ontologies. The results show that only a few studies propose similar artifacts and that there is a need to propose a core WLC ontology to provide the foundation for semantic web application development. The work has been conducted under the modified design science research in [55], namely ontology design science research (ODSR). This methodology provides a thorough process for the ontology conception and creation, integrating surveys and a focus group that guided the requirements definition. The result is an ontology aligning both with the industrial context and the ISO 15686-5 standard, providing a robust artifact for the industry and the academic sector as well. In complement, the use of NeON methodology and its ontology requirement specification document led to the formalization of what practitioners really expect from a WLC analysis through the competency questions defined. Basically, they expressed the need to know what the WLC resulting from the analysis is, what costs compose this WLC, when they appear in the life cycle of the project, and what the financial impacts of choices on those costs are.

The results also demonstrate that WLC use remains limited due to fragmented data, lack of standardization, and the need for specialized knowledge and tools. Additionally, barriers to adoption highlighted by respondents include time constraints and the absence of client demand. Furthermore, the focus group refined these findings, expressing the need to use a WLC data-driven approach rather than a simple indicator. WLC seems to be an opportunity for these professionals' activities to evolve to a more valuable role, switching from simple estimates to economic support for projects. To support this evolution, there is a need for more integrated tools, facilitating data finding among the multiple documentation concerned by the estimation area. The proposed ontology contributes to addressing this issue by proposing a framework with which to integrate multiple heterogeneous information. The study used the ISO 15686-5 as a base of knowledge to structure the ontology framework, allowing a standardization of concepts. In the presented tests, the ontology demonstrated the capability to link different data, assess the WLC, and display all of the detailed results. Moreover, as demonstrated in the results, it can also be extended to other ontologies, meaning its usability in other contexts has been validated. However, this study and this ontology represent only the prototype of a robust solution. There is a need to extend this core framework into a KG to test its applicability in real-world projects. The aim is to connect each deliverable of a project contributing to the WLC calculation. This implies that future work will need to be undertaken in digitalizing the process of a company in order to identify their data requirements and localization. Each WLC data requirement, but also estimation requirement, will need to be crossed with the deliverables of a project to identify where the ontology needs to be connected. In this way, the KG based on the ontology would act as a repository of linked data, where uploaded data will serve as an input to the WLC analysis. This work would reveal the potential of KG application for WLC analysis in construction projects and determine the prospective innovative works that can be developed in implementing promising AI or IoT technologies. Further work will be needed to overcome the absence of risk analysis in this ontological framework. Indeed, risk analysis is crucial in the WLC, according to ISO 15686-5. Retrieving or proposing an ontology assessing the risk of projects will then be needed to complete the present work. The issues acknowledged by the investigation put forward a need for the standardization of existing methodologies to ensure a consistent vocabulary and process between stakeholders. Semantically structuring the WLC domain, the presented ontology can improve accessibility and analysis for professionals. The surveyed professionals confirmed that they are aware of the value of WLC, but that these barriers limit its use as they imply specific knowledge, a need for more advanced tools, and more time, which they lack today.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

WLC	Whole life costing
LCC	Life cycle costing
LCM	Life cycle management
BIM	Building information modeling
PLM	Product lifecycle management
ROI	Return on investment
LD	Linked data
RDF	Resource description framework
RDFS	Resource description framework schema
OWL	Web ontology language
SPARQL	SPARQL protocol and RDF query language

SWRL	Semantic web rule language
URI	Uniform resource identifier
XML	Extensible markup language
KG	Knowledge graph
DSR	Design science research
ODSR	Ontology-based design science research
OSD	Ontology specification document
ISO	International organization for standardization
BOT	Building topology ontology
DiCon	Digital construction ontology
ifcOWL	Industry foundation classes in OWL
AI	Artificial intelligence
IoT	Internet of things
OWLTime	OWL ontology for temporal concepts

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