

Développement d'une approche dynamique du coût global
pour le secteur des actifs bâtis

par

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Développement d'une approche dynamique du coût global pour les actifs bâtis

Adam YOUSFI

RÉSUMÉ

Le coût global est une approche d'estimation financière permettant d'identifier et estimer les coûts du cycle de vie d'un projet. Les recherches tentent de remettre en avant cette méthodologie qui bien que connue de tous, s'avère être une grande oubliée dans les projets. Les motivations derrière cette recherche relèvent tout d'abord d'un enjeu pratique. Le coût global donne la possibilité de prendre en compte de coûts socio-environnementaux issus des externalités des projets. Aussi, la transition numérique du secteur exige une meilleure maîtrise des coûts de construction grâce aux nouvelles technologies de l'information, notamment le Building Information Modeling (BIM). Ces technologies offrent des capacités collaboratives qui facilitent la gestion du cycle de vie. C'est donc une opportunité de remettre en lumière l'approche du coût global dans les discussions. D'un point de vue théorique, il est essentiel de comprendre les barrières persistantes qui entravent son utilisation. Ensuite, il est nécessaire d'appréhender les enjeux d'intégration technologiques dans les projets de construction. La revue de la littérature identifie les technologies de l'internet sémantique comme solution à l'interopérabilité et d'intégration. L'objectif de cette thèse est d'explorer l'utilisation des technologies sémantiques et du BIM comme outils pour soutenir l'intégration systématique du coût global dans les pratiques d'estimation. Le projet de recherche adopte la méthodologie de la Recherche en Science de la Conception. Cette approche méthodologique permet de proposer des solutions à des problèmes pratiques, confrontant à la fois la théorie et la pratique. Adoptant une posture pragmatique, une méthode de collecte de données mixte a permis de récupérer des données quantitatives à travers deux sondages, et des données qualitatives par la réalisation d'entrevues semi-dirigées et d'un groupe de réflexion. Les données ont été récupérées auprès d'estimateurs et économistes de la construction, principalement situés au Canada. Les résultats sont ressortis dans cette thèse par articles au travers de trois papiers revus par des pairs. La première étude clarifie les enjeux de l'approche et souligne l'importance de son caractère interprétatif. Elle propose que les experts en coûts portent le coût global, vu comme une opportunité d'évolution. Le second papier contribue par la translation des connaissances de l'approche en ontologie. Une démonstration présente les capacités de calcul à partir de l'ontologie et discute de ses potentielles utilisations. Dans, le troisième papier une plateforme sémantique est développée pour analyser les estimations de coûts de projet en coût global. Les discussions de la thèse mettent en perspective le besoin d'augmenter l'utilisation du coût global dans les projets et de l'intégrer dans les responsabilités des experts en coûts. Son adoption dépendra cependant d'une évolution culturelle et organisationnelle pour accompagner l'évolution technologique du secteur, et apporter une valeur ajoutée aux projets en optimisant les décisions financières sur les plans économique, environnemental et social.

Mots-clés : Coût global, construction, gestion des coûts, prise de décision, nouvelles technologies de l'information, BIM, technologies sémantiques, ontologie, graphe de connaissances

Development of a dynamic approach to whole life costing for built assets

Adam YOUSFI

ABSTRACT

Whole Life Costing is a financial estimation approach that identifies and estimates the life cycle costs of a project. This research attempts to highlight this methodology, which, although well known, tends to be overlooked in projects. The motivations behind this research are primarily practical. Whole Life Costing makes it possible to take into account the socio-environmental costs resulting from project externalities. Furthermore, the digital transition of the sector calls for improved control of construction costs thanks to the arrival of new information technologies. These technologies, led by Building Information Modeling (BIM), offer various more technological and more collaborative organizational capabilities that facilitate life cycle management. This is therefore an opportunity to bring the whole life costing approach back into the spotlight. From a theoretical point of view, it is essential to understand the persistent barriers that prevent its use. Next, it is necessary to understand the challenges of integrating technology into construction projects. The literature review identifies semantic web technologies as a solution for interoperability and integration. An ontology is a model for representing knowledge that can be interpreted by both humans and machines. The objective of this thesis is to explore the use of semantic technologies and BIM as tools to support the systematic integration of Whole Life Costing into estimation practices. The research project adopts the Design Science Research methodology. This methodological approach makes it possible to propose solutions to practical problems while confronting them in both the theoretical and application domains. Adopting a pragmatic stance, a mixed collection method was used to gather quantitative data through two surveys and qualitative data through semi-structured interviews and a focus group. The data were collected from construction estimators and economists, mainly located in Canada. The results are presented in this thesis in the form of three peer-reviewed papers. The first study clarifies the challenges of the approach and highlights the importance of its interpretative nature. It proposes that cost professionals take responsibility for Whole Life Costing, seen as an opportunity for professional evolution. The second paper contributes by translating knowledge, particularly from ISO 15686-5, into ontology. An initial demonstration in this paper presents the computational capacities based on ontology and discusses its potential uses. In the third paper, a semantic platform is developed to analyze project cost estimates. Ontology is used to model knowledge and calculate whole life costing, demonstrating the benefits of semantic technologies. The thesis discussions highlight the need to increase the use of whole life costing in projects and to integrate it into the responsibilities of cost engineers. Its adoption, however, will depend on a cultural and organizational shift allowing estimators and cost engineers to be trained and to bring added value to projects by optimizing financial decisions across economic, environmental, and social dimensions.

Keywords: Whole Life costing, Construction, cost management, decision-making, new information technologies, BIM, semantic technologies, ontology, knowledge graph

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LISTE DES ABRÉVIATIONS, SIGLES ET ACRONYMES

ACG	Analyse du coût global
ACV	Analyse du cycle de vie
AEÉCQ	Association des Estimateurs et Économistes du Québec
AI	Artificial Intelligence
ASTM	American Society for Testing and Materials
BCF	BIM Collaboration Format
BIM	Building Information Modeling
BOT	Building Topology Ontology
bSDD	buildingSMART Data Dictionary
DiCon	Digital Construction Ontology
DSR	Design Science Research
IFC	Industry Foundation Classes
IDS	Information Delivery Specification
IDM	Information Delivery Manual
IoT	Internet of Things
IRR	Internal Rate of Return
ISO	International Organization for Standardization
ifcOWL	Industry Foundation Classes in OWL
KG	Knowledge Graph
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCM	Life Cycle Management

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LD	Linked Data
NPV	Net Present Value
NS	Net Savings
ODS	Ontology Design Specifications
ODSR	Ontology-Based Design Science Research
OSD	Ontology Specification Document
OWL	Web Ontology Language
Open API	Open Application Programming Interface
PB	Payback Period
PLM	Product Lifecycle Management
RDF	Resource Description Framework
RDFS	RDF Schema
ROI	Return on Investment
RSC	Recherche en science de la conception
SIR	Savings-to-Investment Ratio
SPARQL	SPARQL Protocol and RDF Query Language
SQWRL	Semantic Query-Enhanced Web Rule Language
SWRL	Semantic Web Rule Language
UCM	Use Case Management
URI	Uniform Resource Identifier
VPN	Valeur présente nette
WLC	Whole Life Costing

XML Extensible Markup Language

INTRODUCTION

Un projet de construction représente une initiative importante pour un maître d'ouvrage, qui s'engage souvent avec une part non négligeable de son capital. La maîtrise des coûts vise à respecter le budget de construction, mais devrait aussi prévoir les besoins liés à la vie utile du bâti. C'est pourquoi le client doit s'entourer de personnes compétentes pour assurer la viabilité financière de son projet. En effet, un bâtiment dispose d'une durée de vie typique d'une centaine d'années (Andersen & Negendahl, 2023). Au cours de cette période, l'édifice est donc un bien qu'il faut garder en santé afin d'atteindre cette durée de vie tout en profitant de ses fonctions initialement souhaitées (Méquignon & Ait Haddou, 2014). Il a déjà été prouvé que des choix de conception réfléchis dès les premières étapes du projet assureront la pérennité de la construction, tout en limitant des surcoûts opérationnels, mais aussi des impacts environnementaux (Bauer, Möhle, & Schwarz, 2010 ; Kishk et al., 2003). Prévoir les dépenses à long terme est donc essentiel pour valoriser son investissement et réaliser de réelles économies. Néanmoins, bien que des efforts sont de plus en plus notables, il est aujourd'hui très peu commun de regarder au-delà du coût d'investissement lors des conceptions de projets (Gluch, Gustafsson, Baumann, & Lindahl, 2018).

Dans le but de maîtriser les coûts du cycle de vie des projets, l'analyse du coût global (ACG) a démontré être une approche pertinente pour offrir une vue systémique des coûts (Farr & Faber, 2018). Cette approche assure une pensée en cycle de vie des investissements, considérant les coûts de toute la durée de vie de l'actif, ainsi que ceux de ses impacts sur son environnement pour la société (Pelzeter, 2015). Ce procédé peut donc être profitable pour un maître d'ouvrage cherchant à maîtriser et optimiser les coûts de son projet. Cependant, l'ACG est encore peu connue dans son entièreté. La majorité des projets sont encore basés sur des analyses de rentabilités avec des indicateurs plus simples, tels que le taux de retour sur investissement (Gluch et al., 2018). Ces indicateurs, bien que révélateurs de la pertinence du projet, sont parfois utilisés de manière très simpliste sans tenir compte du contexte de calcul (Botchkarev & Andru, 2011). L'ACG comme approche complémentaire, permet de

considérer le projet dans son ensemble, dans sa temporalité et d'intégrer à l'analyse économique tout élément pertinent et monétisable.

Considérant le grand nombre de données issues d'un projet de construction, nous pouvons rapidement nous apercevoir que le coût global est une approche laborieuse aux yeux des économistes (Cole & Sterner, 2000). L'estimation seule des coûts de construction est déjà une tâche demandant un certain effort, de ce fait, imaginer considérer l'ensemble des coûts du cycle de vie du projet peut sembler très ardu. Par ailleurs, un projet de construction est composé de divers acteurs qui produisent des données variées, qu'il faut identifier et obtenir l'accès. La tâche de l'analyste peut vite se retrouver alors être, pour la majorité du temps qu'il dispose pour sa mission, de la collecte de données, laissant peu de place à l'interprétation et au conseil dans les prises de décisions. Toutefois, le contexte actuel du secteur amène de nouveaux horizons pour ces types d'approches riches en données. En effet, les nouvelles technologies de l'information prennent de plus en plus de place dans les pratiques.

L'arrivée de la Modélisation des Information du Bâtiment, communément appelé Building Information Modeling, (BIM), offre des perspectives de gestion de données novatrices. La digitalisation des projets permet de mettre en place des processus automatisés de traitement des données, réduisant ainsi significativement le temps nécessaire, mais aussi les erreurs de certaines tâches (Barnes, 2019). Aussi, parmi les nouvelles technologies de l'information, l'un des fondements qui permettra l'optimisation de ces procédés est celui du web sémantique. Le web sémantique apporte de nouvelles pratiques standardisées sur l'échange et la contextualisation des données, les reliant à des concepts structurés leurs correspondant, pour organiser des domaines de connaissances (Asfand-e-yar, Kučera, & Pitner, 2014). De la sorte, les agents informatiques opérant selon une approche sémantique ont la capacité de raisonner, permettant le traitement et l'exploitation des données plus efficaces (Berners-Lee & Hendler, 2001). Ainsi, aujourd'hui est un moment décisif pour la mise en place de systèmes de gouvernance guidant l'industrie vers une innovation responsable, offrant des

biens et services améliorant les activités du secteur, respectant l'environnement et la planète (Voegtlin & Scherer, 2017).

Le projet de recherche présenté dans cette thèse par articles a pour objectif d'explorer l'utilisation des technologies sémantiques et du BIM comme outils pour supporter l'intégration systématique du coût global dans les pratiques d'estimation. Trois articles sont présentés afin d'assurer l'atteinte de cet objectif. Chaque article apporte sa propre contribution et peut être considéré individuellement, mais l'ensemble présente une suite logique qui permet de répondre à la question de recherche traitée dans cette thèse : ***Quelles opportunités offrent le contexte socio-technologique actuel des projets de construction pour adopter le coût global dans les pratiques d'estimation ?***

La recherche a été conduite selon la méthodologie de la science de la conception. La collecte de données a été réalisée grâce à une méthode mixte auprès d'estimateurs et économistes. L'analyse de données a consisté en une analyse systématique et itérative afin d'arriver au développement de l'artefact. La proposition a ensuite été évaluée sur sa technologie mais aussi sur sa pertinence auprès du terrain. Les contributions de la recherche sont à la fois théoriques et pratiques. La première analyse de données a permis la proposition d'un cadre d'intégration du coût global dans les pratiques en réponse aux enjeux d'adoption identifiés. Basé sur les réflexions de cette théorie, la contribution principale de cette thèse est une ontologie du coût global, dont les capacités sont démontrées à travers son application. L'ontologie couvre les principes clés du coût global, représentant ses concepts fondamentaux et les relations qui les structurent. Offrant déjà la possibilité de nourrir un programme de calcul du coût global, l'ontologie a ensuite été rendue accessible à travers un prototype de plateforme d'analyse. Cette plateforme facilite l'exploration des données de coûts du cycle de vies de projets et l'interrogation de celles-ci. Ainsi l'utilisateur a la possibilité d'investiguer les impacts économiques de son projet sous différentes perspectives. Considérant le contexte de la transition numérique du secteur de la construction, cette plateforme a été conçue pour fonctionner à partir, mais aussi pour, des modèles BIM servant pour la collecte de données mais aussi comme répertoires de résultats.

Le premier chapitre offre une vue d'ensemble du projet de recherche. Il présente ses motivations pratiques et théoriques, sa conception et ses résultats. Une problématique est formulée et des objectifs de recherche sont posés. La conception du projet de recherche est décrite, incluant les fondements théoriques et la méthodologie. Les trois articles composant la thèse sont résumés et leurs contributions sont présentées. Chaque article est ensuite inclus dans son intégralité dans les chapitres suivants. Le dernier chapitre présente une discussion sur la méthodologie de la recherche et les résultats, les contributions du travail ainsi que les opportunités pour des travaux futurs. Pour terminer, une conclusion générale est tirée.

CHAPITRE 1

MOTIVATIONS, CONCEPTION ET RÉSULTATS DE LA RECHERCHE

1.1 Introduction

Ce premier chapitre présente les fondements de la recherche menée dans cette thèse. Tout d'abord les motivations personnelles et pratiques sont formulées. Ensuite, les motivations théoriques décrivant les concepts théoriques explorés dans cette thèse sont exposés. Ainsi, les concepts du coût global et son historique, ceux du BIM, et des technologies du web sémantique sont décrits sous la forme d'une revue de la littérature. Le problème de recherche est ensuite énoncé, puis une question de recherche est proposée. Pour finir, les positions ontologique, épistémologique et méthodologique de la recherche sont présentées puis traduites dans l'application de ce projet. Finalement, la structure de la thèse présente les différents articles scientifiques accompagnés de leurs contributions.

1.2 Motivations personnelles et pratiques

L'idée d'explorer l'ACG comme sujet de recherche est issu d'un problème observé depuis mes premiers stages en industrie, puis vécu lors d'une expérience en tant qu'assistant environnemental à la maîtrise d'ouvrage dans une municipalité : la pensée que l'aspect environnemental est un élément trop coûteux pour le prendre en compte dans un projet. Ayant eu pour mission de garantir la qualité environnementale des projets, j'ai très vite, et souvent, été heurté à la problématique budgétaire, menant au « fait » que l'aspect environnemental était un surcoût non prioritaire. Bien qu'aujourd'hui cette conscience évolue grâce aux multiples appels à l'action, une certaine résistance persiste. Certains projets ne sont par exemple engagés dans des processus de certification que dans la volonté de gagner en visibilité. D'autres aussi, respectent de justesse les réglementations mais gardent une vision d'économie financière seulement. Dans l'idée de parler le même « langage » que ces investisseurs qui, à juste titre, limitent les surinvestissements, j'ai exploré la notion de coût global pour tenter de convaincre.

Convaincre a été jusqu'à présent le mot phare qui a guidé mes actions dans ce domaine. Mon objectif, qui se poursuivra certainement après cette thèse, est de convaincre que chaque projet devrait être pensé et conçu durablement. Par le terme « durable » je n'entends pas seulement le terme « Environnement » mais la notion plus large du Développement Durable, portée par ses trois fameux piliers « Environnement », « Économique » et « Social ». C'est pourquoi l'approche du coût global, qui dans ses principes offre une vision de l'ensemble des coûts d'un projet et de ses impacts, est adaptée à cette mission. En effet, la proposition de cette approche au sein de la municipalité, même si elle s'était limitée à la prise en compte de coûts d'exploitation et maintenance, s'est montrée très encourageante et invitait aussi à plus de collaboration entre les différents services. C'est ainsi que j'ai souhaité continuer d'explorer en profondeur les rudiments de cette approche à travers cette recherche, dans le but de contribuer modestement à propager l'adoption d'une réflexion systémique des projets de construction. Une seconde motivation ayant poussée la réalisation de cette thèse, est la volonté d'entrer dans le monde des nouvelles technologies. Conscient de l'évolution technologique rapide de toutes les industries, et n'ayant que peu témoigné de leur application avant ce projet, cette étude doctorale a été une occasion d'explorer ce sujet afin d'en comprendre les opportunités mais surtout les réels enjeux impliqués pour le secteur de la construction.

1.3 Motivations théoriques

1.3.1 Estimer les coûts d'une construction

L'estimation est l'action de prédire ou prévoir un coût, autrement dit de construire un modèle réunissant des variables qui nous permettra d'obtenir une valeur (Roy, 2008). Prédire un coût, est l'utilisation de ce modèle à un temps donné, par exemple au moment de la construction. Prévoir un coût est l'estimation de ce coût dans un temps futur avec une projection des paramètres (Runge & Zmeureanu, 2019). Dans un projet de construction, un édifice est un système complexe, évoluant dans un environnement incertain. Chaque projet est unique, présentant des objectifs, besoins et contextes chaque fois différents (Crotty, 2011). Il est donc difficile d'établir des modèles standards pour prévoir l'évolution des coûts

des bâtiments. Pourtant, plus un projet est grand, plus les responsabilités du propriétaire seront conséquentes. Il a donc tout intérêt à comprendre les implications de son bâtiment pour optimiser la valeur future du projet et donc sa réussite (Olsson, Johansen, Alexander Langlo, & Torp, 2008).

1.3.1.1 Les coûts de construction

Les coûts de construction comprennent toutes les dépenses liées à la réalisation du bâtiment, incluant les travaux, les coûts de chantier, les honoraires professionnels, les frais généraux et les imprévus. Des approches sont aujourd'hui normalisées afin de faciliter ces démarches d'estimation. Trois catégories de techniques d'estimation sont communément utilisées afin d'estimer les coûts, à savoir l'estimation paramétrique, la méthode analogue ou encore l'estimation détaillée (Farr & Faber, 2018). En début de projet, l'estimation sera dite conceptuelle, et aura pour but de prévoir les coûts du projet de construction alors que peu d'éléments sont connus. On utilisera alors la méthode analogue pour comparer le projet en se basant sur données historiques, ou l'estimation paramétrique pour appliquer des ratios de coûts unitaires issus de projets similaires (AASHTO, 2013). À mesure que le projet se précise, on réalise une estimation détaillée en décomposant le projet d'abord en éléments, puis en composants. L'estimation finale permet alors de prédire les coûts de construction à partir de l'ensemble des variables connues, notamment les coûts de matériaux et de main-d'œuvre (Reddy Anireddy, 2024).

1.3.1.2 Les coûts post-construction

Les coûts post-construction couvrent une plus longue période, comprenant les coûts d'exploitation et maintenance, les remplacements d'équipements, les réparations majeures, les coûts énergétiques, ainsi que les coûts de fin de vie comme la déconstruction. Ils sont aussi plus simples à déterminer lorsque tous les équipements et composants sont connus. Quatre approches sont utilisable pour les déterminer (Ottoman, Nixon, & Lofgren, 1999) :

- L'approche fondée sur la valeur des installations, estime les coûts d'entretien et de réparation en fonction du coût de construction ou de la valeur de remplacement. Cette approche est basée sur l'hypothèse que la valeur d'une installation reflète sa taille et sa performance, qui sont directement proportionnelles aux besoins de maintenance.
- L'approche fondée sur des formules, utilise des variables basées sur des caractéristiques physiques du bâtiment, et parfois intangibles (âge, superficie, type d'installation ou encore climat) pour déterminer les besoins annuels de maintenance.
- L'approche du cycle de vie, décompose les installations en systèmes et composants, estimant les besoins futurs en entretien et réparation. L'analyse du cycle de vie détermine les fréquences d'entretien et de remplacement, puis les coûts associés sont estimés.
- L'approche fondée sur l'état des installations, est applicable pour estimer les coûts d'entretien et de réparation, ou la durée de vie utile restante. Les méthodes basées sur les déficiences ciblent l'entretien immédiat, tandis que celles basées sur la durée de vie utile soutiennent la planification à long terme.

Enfin, les coûts de fin de vie sont généralement prévisionnés grâce aux mêmes méthodes que celles des coûts de construction, suite à la décision du mode de disposition du bâti, pouvant être démolé ou déconstruit, et des techniques mises en œuvre pour le réaliser (Zahir, 2015).

Malgré la rigueur et l'expérience de l'estimateur, cet exercice garde une part d'incertitude. Des variables telles que la qualité d'exécution de la construction, l'évolution de la condition physique du bâti ou encore les fluctuations de prix, sont incontrôlables lors de l'estimation (Rauzana, 2018). Ces incertitudes sont souvent couvertes par des méthodes déterministes, où une seule valeur est conservée, à laquelle des frais de contingences correspondant à un pourcentage du prix de construction sont ajoutés (Mok, Tummala, & Leung, 1997). Des pratiques plus avancées existent pour quantifier les risques grâce à des méthodes de simulation, telles que la méthode Monte Carlo, les arbres de décision, ou les analyses fondées sur la logique floue. Ces méthodes permettent de définir un éventail de coûts associés de

probabilités d'occurrence, supportant les décisions dans les projets (Abdou, Lewis, & Alzarooni, 2004 ; Mok et al., 1997 ; Sadeghi, Fayek, & Pedrycz, 2010).

1.3.2 Historique de l'approche du coût global

Afin de comprendre le contexte du coût global, cette section aborde son historique pour en déchiffrer l'évolution. L'intérêt envers les coûts de maintenance n'est pas nouveau. En effet, nous pouvons trouver deux études traitant des coûts d'exploitation dès 1899, toutes deux en provenance de New York City dans (Sever & Fliess, 1899) et (Moses, 1899) portant respectivement sur le secteur automobile et les bâtiments. L'intérêt pour les coûts du cycle de vie dans la construction est donc aussi présent depuis très longtemps et aurait pu évoluer de la même manière que dans d'autres secteurs. Toutefois, en cherchant sur cette thématique un peu plus tard, une différence et un retard se font déjà ressentir. Quelques années plus tard, nous pouvons déjà retrouver une proposition de standardisation d'évaluation des coûts d'exploitation de centrales électriques afin d'en définir leurs efficacité (Stott & Gorsuch, 1913). Le secteur industriel a donc rapidement cerné les enjeux des phases d'exploitation car leurs infrastructures sont vues comme un produit à rentabiliser. Dans une même période, on peut remarquer que le secteur ferroviaire est aussi dans une démarche de maîtrise des coûts de maintenance (Jones, 1915). Cet intérêt peut s'expliquer du fait que ces infrastructures nécessitent un entretien constant car une négligence de l'état des rails peut être fatale pour la sécurité des passagers.

À l'inverse, pour le secteur de la construction, l'heure ne semblait pas en être à l'élaboration de solutions. Nous avons trouvé un article de 1914 (Aronovici, 1914) discutant des différents facteurs de coûts qui composent un projet de construction. Cette étude ne propose pas de solution à notre sujet ici, mais faisait déjà le constat que les besoins immédiats avaient le dessus sur les besoins futurs et l'optimisation de la maintenance du bâti. En comparaison avec les autres industries, celle du bâtiment ne semble pas éprouver de pression quelconque qui justifierait une réflexion approfondie des coûts de maintenance. Il semble qu'aucune

étude n'ait été menée sur le coût global pour les bâtiments à cette époque. Seules des études portant sur les coûts de maintenance dans d'autres secteurs d'activité sont disponibles.

Ce n'est que vers 1950 qu'une approche s'est développée pour les bâtiments, sous le nom de « cost-in-use », puis a été formalisée telle que nous la connaissons aujourd'hui en 1960 (B. H. Goh & Sun, 2016). Cependant l'approche n'aurait connu de réel intérêt seulement après la crise de l'énergie de 1973, éveillant les consciences sur l'importance de la conception pour la réduction des coûts d'exploitation (B. H. Goh & Sun, 2016). Suite à cela, l'intérêt pour le coût global s'est développé et plusieurs guides pratiques ont pu voir le jour (B. H. Goh & Sun, 2016 ; Kishk et al., 2003). Aujourd'hui, il existe des normes internationales qui orientent l'ACG, telles que les normes ISO (International organization for standardization) 15686-5 et ASTM (American Society for Testing and Materials) E917-11. Comme pour les autres industries, c'est donc une situation critique, à travers la crise de l'énergie, qui a éveillé l'attention pour une approche à long terme. Cependant, l'industrie est restée réticente à son utilisation car les coûts d'investissement sont traditionnellement séparés des coûts de maintenance, la méthodologie et la collecte de données sont complexes et chronophages et les responsabilités des coûts post-construction n'étaient pas clairement définies (Kishk et al., 2003).

Malgré cela, l'ACG est aujourd'hui remis dans les sujets d'intérêts pour deux raisons : le développement durable en réponse à l'urgence environnementale mondiale, et la technologie, qui à l'inverse, sonne plus comme une opportunité. En effet, dès le début des années 2000, l'utilisation de l'approche est très vite exploitée dans le milieu académique pour compléter des approches durables comme celle de l'analyse en cycle de vie (ACV) (B. H. Goh & Sun, 2016). Puis, des certifications environnementales telles que BREEAM en 2008, HQE en 2010 et LEED en 2013 ont intégré le coût global comme critère d'évaluation. Depuis cette période, le coût global commence à se disséminer dans l'industrie mais ne fait toujours pas partie des usages courants. Il semblerait que l'approche soit davantage utilisée dans les projets publics, et que le secteur privé manque de cas d'application en raison d'un manque de demande de la part des investisseurs (Higham, Fortune, & James, 2015).

1.3.3 Aperçu de l'approche en coût global

1.3.3.1 Définition

Dans sa forme la plus simple, l'ACG est composée de coûts présents et de coûts futurs (Farr & Faber, 2018). L'ACG est une approche d'estimation financière qui permet de prendre en compte l'ensemble des coûts, directs et indirects, d'un projet sur l'ensemble de son cycle de vie (Farr & Faber, 2018). Aujourd'hui, l'approche est régie par la norme ISO 15686-5 comme « la prise en compte des coûts pertinents depuis la phase d'acquisition jusqu'à la démolition » (ISO, 2017). De son côté, la norme ASTM E917-17 définit l'ACG comme « la somme de tous les coûts pertinents associés à la possession et à l'exploitation d'un bâtiment ou d'un système de bâtiment sur une période donnée » (ASTM International, 2017). Cette comparaison intéressante de ces deux normes présentées dans le Tableau 1.1, permet déjà de mettre en avant une certaine disparité au niveau de la perception de l'approche.

Tableau 1.1 Comparaison des normes ISO 15686-5 : 2017 et ASTM E-917-17

Norme	ISO 15686-5 : 2017	ASTM E917-17
Définition	Coût global = coût d'un actif ou de ses parties tout au long de son cycle de vie, tout en répondant aux exigences de performance.	La méthode du coût global mesure, en valeur actualisée ou en valeur annuelle, la somme de tous les coûts pertinents associés à la possession et à l'exploitation d'un bâtiment ou d'un système de bâtiment sur une période donnée.
	Coût global étendu= ensemble des coûts et avantages initiaux et futurs significatifs et pertinents d'un actif, tout au long de son cycle de vie, tout en répondant aux exigences de performance	

Tableau 1.1 Comparaison des normes ISO 15686-5 : 2017 et ASTM E-917-17 (suite)

Objectifs	Quantifier les coûts du cycle de vie pour la prise de décision ou un processus d'évaluation, et devrait inclure des données provenant d'autres analyses (ACV, évaluation de la conception, sécurité, fonctionnalité, régulation)	Comparer des alternatives de conception de bâtiments ou systèmes qui répondent aux mêmes exigences fonctionnelles
Utilisations	Comparaison de scénarios d'investissements et d'alternatives qui répondent aux exigences du client	Déterminer si le coût initial plus élevé d'un bâtiment ou d'un système de construction est économiquement justifié par des réductions de coûts futurs.
Méthodes de calcul	Valeur présente nette	Valeur présente nette : actualisation de l'ensemble des coûts au temps de base définit Valeur annuelle: Coût annuel uniforme
Hypothèses	<p>Période d'analyse: exigences clients ou durée de vie du système</p> <p>Inflation: À déterminer avec une analyse sensitive.</p> <p>Taux d'actualisation: Pour le secteur privé, il doit représenter le rendement du coût d'opportunité. Pour le secteur public, doit être déterminé par le gouvernement. Un TA entre 0 et 4% est généralement utilisé.</p> <p>Taxes et subventions: à inclure car cela peut influencer les prises de décisions.</p> <p>Variation des coûts à travers le temps: pénuries de mains d'œuvres/matériaux</p> <p>Externalités: bénéfiques/coûts socio-environnementaux, revenus</p>	<p>Période d'analyse: Selon les exigences client ou la durée de vie du système (doit être la même pour calculer la VP dans les catégories de coûts)</p> <p>Inflation: le calcul peut être réalisé en dollars constants sans inflation générale ou en dollars courants avec une inflation cintégrée dans le taux d'actualisation.</p> <p>Taux d'actualisation: doit refléter la considération du client pour la valeur du temps. Si le taux n'est pas régi par une institution, choisir le taux de rendement du coût d'opportunité</p> <p>Complétude: considérer toutes les alternatives appropriées et les facteurs pertinents</p> <p>Impôts sur les revenus: inclure les ajustements pour les investissements soumis à l'impôt sur le revenu</p>

Tableau 1.1 Comparaison des normes ISO 15686-5 : 2017 et ASTM E-917-17 (suite)

Données de coûts	<ul style="list-style-type: none"> -Acquisition: site, travaux temporaires, conception/ingénierie, réglementation, planification, construction, frais de mise en service, administration ; -Coûts d'exploitation et d'entretien : considérer la performance des éléments, estimation des fins de vies conformément aux régulations, travaux de maintenances requis, pertes de confort, coûts de consommations, inspections, nettoyage, coûts indirects possibles selon les cas ex: coûts d'arrêts des activités -coûts de fin de vie: mise à disposition, valeur résiduelle ou démolition 	<ul style="list-style-type: none"> -L'investissement initial, y compris les coûts de planification, de conception, d'ingénierie, d'acquisition et de préparation du site, de construction, d'achat et d'installation ; -Les frais de financement ; -Coûts d'exploitation et d'entretien récurrents annuels et non annuels ; -Coûts d'utilisation fonctionnelle ; Coûts de remplacement des immobilisations ; Valeur de revente
Analyse des risques	Monte Carlo Analyse sensitive	Monte Carlo Analyse sensitive Analyse de probabilité

La norme ISO considère deux facettes du coût global à travers le « coût global » et « coût global étendu », mettant en avant son rôle dans la prise en compte de la durabilité. La définition de la norme ASTM ne fait pas de différence terminologique, mais semble tout de même considérer le coût global étendu, laissant la liberté aux économistes de décider de la portée de l'analyse. Cette légère différence se retrouve au niveau des objectifs, où la norme ISO précise que l'ACG devrait inclure d'autres analyses telles que l'ACV. Mais de manière générale, les deux normes se rejoignent pour dire que le but est de comparer deux solutions en estimant leurs coûts du cycle de vie. Cette différence de la considération de l'environnement est présente dans la définition des hypothèses où l'ISO évoque explicitement la notion d'externalités, définie comme les « *coûts ou bénéfices quantifiables survenant quand les actions engagées par des organisations ou des personnes ont des impacts sur d'autres intervenants qu'eux-mêmes* » (ISO, 2017). Au niveau méthodologique,

les normes se rejoignent avec l'utilisation de la valeur présente nette (VPN). Enfin, les deux normes considèrent des catégories de coûts semblables et suggèrent l'utilisation d'analyse des risques pour compléter les résultats.

1.3.3.2 Objectifs du coût global

Depuis ses premières utilisations, cette technique a été utilisée pour déterminer les meilleures alternatives pour les projets (Cole & Sterner, 2000). La norme ISO 15686-5 :2017 précise que le rôle du coût global est de quantifier les coûts du cycle de vie pour alimenter un processus de décision ou d'évaluation. Ainsi, il peut supporter la prise de décision en monétisant la performance d'une nouvelle solution, aidant à l'allocation des ressources du projet, mais aussi en fournissant des données pour des négociations (Kishk et al., 2003 ; MEDDAT, 2009). Dans la pratique, le coût global apparaît comme un outil d'aide à la décision pour aider à sélectionner des projets, des conceptions ou des éléments de construction alternatifs, mais aussi comme un outil supportant la prévision des tâches et des coûts liés à l'exploitation et maintenance (Swaffield & McDonald, 2008). Considérant le contexte d'urgence climatique actuel, sa capacité à relier l'aspect durable à l'aspect économique est souvent mise en avant. L'approche peut être considérée comme une méthode d'aide à la conception durable, pouvant opposer le fait que les solutions environnementales sont des obstacles économiques, et ce, surtout à court terme (Hunkeler & Rebitzer, 2003).

1.3.3.3 Bénéfices de l'approche pour les projets

Un certain nombre d'études ont établi les bénéfices de l'approche, qui ne sont aujourd'hui plus à prouver. Ces avantages se retrouvent particulièrement dans l'aide à la décision, la mesure de performance, la communication, la compréhension des coûts et l'amélioration continue (Ellram, 1995). L'approche donne la possibilité d'accepter ou rejeter une décision d'investissement grâce donnant la capacité d'identifier les conceptions et les paramètres les plus viables à long terme (ex. la localisation du projet) (Ruegg & Marshall, 1990). Cette approche peut s'appliquer tant au niveau du projet, qu'à un niveau de détail plus précis, sur des éléments qui peuvent avoir une influence significative sur le cycle de vie d'un projet

(Mistry, Koffler, & Wong, 2016). Aussi, grâce au coût global, les décideurs ont l'opportunité d'intégrer une analyse socio-environnementale et d'obtenir de nouveaux facteurs de comparaison, permettant de rechercher une balance entre bénéfices économiques, environnementaux et sociaux (Meng & Harshaw, 2013). Le coût global, tel que défini par l'ISO 15686-5, améliore l'évaluation des projets en identifiant les catégories de coûts les plus élevées, en explicitant des coûts cachés et en facilitant l'amélioration continue des fournisseurs (Hurkens, 2006 ; Sousa, Dias-Ferreira, Vaz, & Meireles, 2018). Son utilisation, peut aussi se faire de manière partagée entre les parties prenantes, influençant la communication, la transparence et la confiance dans les projets (Zachariassen & Arlbjørn, 2011).

1.3.3.4 Barrières à l'utilisation de l'approche

Bien que l'approche présente de nombreux bénéfices, son utilisation reste modérée. Trois grandes limites se distinguent : la culture, la formation et les ressources (Ellram, 1995 ; Roda, Macchi, & Albanese, 2020). D'après l'étude de Roda (2020), le premier obstacle qui peut être rencontré est au niveau humain, c'est-à-dire la culture au sein de l'entreprise montrant une résistance aux changements. L'approche pouvant être jugée très complexe entraîne parfois une réticence de la part de l'entreprise, qui ne se sent pas encore assez mature pour l'adopter. De plus, les gestionnaires ont tendance à se concentrer sur la réalisation d'économies sur l'investissement des projets et manquent d'outils d'aide à la prise de décision sur le long terme (Roda et al., 2020). Aussi, Cole (2000) ajoute pour cause la motivation des personnes à mener cette approche qui nécessite plus de temps et d'efforts (Cole & Sterner, 2000). Dans la majorité des cas, dans le secteur publique, l'approche est portée par les politiques des villes et dans le secteur privé, par les demandes des clients. À part si cela est formalisé contractuellement, cette démarche ne sera presque jamais volontaire (Olubodun, Kangwa, Oladapo, & Thompson, 2010).

Au niveau des ressources, le manque de données est le point le plus important dans ces barrières car le calcul dépend fortement de l'accessibilité, la qualité et la précision de ces

données (Cole & Sterner, 2000). Seulement, ces données peuvent parfois être inconsistantes et celles de matériaux et composants peuvent manquer d'informations sur leur cycle de vie (El-Haram, Marenjak, & Horner, 2002 ; Mistry et al., 2016). Une des raisons à cela est la fragmentation de l'industrie qui entraîne des pertes d'informations, mais aussi au fait que l'analyse nécessite de prévoir des coûts loin dans l'avenir, ce qui peut être difficile dans certains cas (Kishk et al., 2003). Aussi, la collecte des données pour établir la base de données des analyses est reconnue pour être la tâche la plus chronophage et difficile, ce qui peut limiter l'application de cette technique dans les projets (Farr & Faber, 2018 ; Soust-Verdaguer, Llatas, & García-Martínez, 2017).

La dernière limite se trouve au niveau méthodologique. L'approche peut être perçue comme complexe avec laquelle de nombreux estimateurs ne sont pas à l'aise, ce qui peut les faire hésiter à pratiquer le coût global (Ellram, 1995 ; Kehily & Underwood, 2017). Le manque de méthodologie signifie aussi que les utilisateurs doivent développer leur propre façon d'entreprendre cette approche, ce qui entraîne un gaspillage du temps et des ressources (Seyis, 2020).

1.3.4 Paramètres du coût global

Dans cette section, nous passerons en revue l'ensemble des paramètres et variables du coût global exerçant une influence sur les résultats.

1.3.4.1 La durée de vie du projet

Le premier paramètre indispensable est celui de la période d'analyse. La période choisie doit être suffisamment longue et réaliste pour montrer les impacts pertinents de l'investissement initial sur le futur (Pelzeter, 2015). Les chercheurs s'accordent sur le fait qu'une trop longue période d'analyse augmente l'imprévisibilité des événements (Kishk et al., 2003). Du côté de la norme ISO 15686-5, il est recommandé de choisir une période basée sur les exigences du client. La période peut aussi être choisie de manière à correspondre à la période d'occupation ou une responsabilité contractuelle. Cette durée doit également tenir compte de la durée de

vie attendue des éléments majeurs du bâtiment, condition souvent déterminante pour établir l'horizon d'analyse (Daniotti & Spagnolo, 2007). D'un point de vue économique, il est important que cette période couvre les phases où les coûts significatifs apparaissent, notamment ceux liés à l'exploitation et maintenance, qui représentent la majeure partie des coûts sur le cycle de vie (Ji, Lee, & Yi, 2021). Cependant, la durée de vie réelle des bâtiments peut diverger fortement de leur durée de vie nominale pour des raisons contextuelles, comme l'état du bâtiment ou les stratégies de re planification urbaines, ce qui rend le choix d'un horizon d'analyse standardisé difficile (G. Liu, Xu, Zhang, & Zhang, 2014). Ainsi, la période d'analyse ne peut être arbitraire, mais doit refléter à la fois les intentions initiales, les exigences contractuelles, la durée de vie fonctionnelle des composants et les usages prévisibles du bâtiment. En pratique, la durée retenue pour l'analyse correspond généralement à la valeur minimale issue de ces approches, afin d'éviter une surestimation des performances à long terme.

1.3.4.2 Le taux d'actualisation

Actualiser les coûts est une manière d'évaluer les conséquences d'investissements dans un futur qui est par définition empli d'incertitudes. Le taux d'actualisation reflète la valeur qu'un décideur attribue aujourd'hui à des résultats qui se produiront dans le futur, traduisant sa préférence pour des bénéfices à court ou long terme (Creedy & Passi, 2018). La norme ISO 15686-5 (2017) estime que ce taux est généralement choisi entre 0 et 4%, et il peut être le taux d'intérêt d'un prêt d'investissement ou encore le taux d'inflation. Cependant, la nature du projet impactera ce projet, un taux d'actualisation trop bas favorisera les solutions à long terme, et inversement. La particularité de ce paramètre est qu'il reste très subjectif et se base principalement sur l'expérience, le savoir et l'intuition de celui qui le choisit (Olubodun et al., 2010). Gollier (2012) indique que le TA peut aussi être égal aux coûts d'opportunités ou aux coût moyen pondéré du capital correspondant à un taux de rentabilité attendu pour un investissement. Une solution proposée par Weitzman (2010) est d'appliquer un TA décroissant qui va permettre de prendre en compte les incertitudes futures dans le calcul aujourd'hui. Ainsi, comme un TA bas favorise le long terme, et que la probabilité qu'un

évènement majeur augmente avec le temps, les ressources disponibles pour couvrir ces évènements seront maximisées. En prenant le cas d'énergies renouvelables, Leskinen (2020) montre qu'il est aussi possible d'utiliser le rendement des propriétés défini par le marché immobilier qui a pour avantage de prendre en compte plusieurs risques tels que la demande en logement, l'âge ou la condition de la propriété. Pour finir, Ardian (2018) propose de calculer un TA dynamique, en prédisant un TA spécifique à chaque année. Pour cela, l'auteur applique le processus stochastique « Ornstein-Uhlenbeck » qui va permettre de trouver des taux d'intérêts annuels pour chaque année dans une période choisie. Ces taux sont ensuite appliqués au calcul du taux d'actualisation grâce à la méthode du coût moyen pondéré du capital. Le choix du taux d'actualisation est un sujet fort débattu et délicat tant son impact est important dans les projets. Actualiser les coûts est une manière de déterminer un équilibre intergénérationnel entre la consommation des ressources aujourd'hui et le futur bien-être de chacun (Gollier, 2012 ; Weitzman, 1998).

1.3.4.3 Les types de coûts

1.3.4.3.1 Les coûts directs

Les coûts directs désignent les dépenses engagées spécifiquement pour la réalisation physique du projet, telles que la main-d'œuvre, les matériaux, les équipements, les transports ou l'usage des installations sur le site (AASHTO, 2013). Leur importance est centrale, car ils représentent la majorité du budget initial et définissent donc la constructibilité du projet. C'est la raison pour laquelle cette catégorie est l'obstacle premier de l'ACG. Pourtant, ils constituent le point de départ de l'analyse, et vont influencer les coûts futurs, car les choix faits en début de projet vont affecter les coûts futurs de l'actif (Dwaikat & Ali, 2018).

1.3.4.3.2 Les coûts indirects

Contrairement aux coûts directs, les coûts indirects sont plus difficiles à déterminer et quantifier. Les coûts indirects désignent les dépenses qui ne sont pas allouables à un poste de travail lié à la réalisation de la construction. Durant la phase de construction ces coûts

peuvent inclure des études, des taxes, des coûts d'administration ou encore des coûts imprévus (Lawton, 1952). Du point de vue du coût global, ils vont permettre de modéliser les scénarios à long terme. Leur mauvaise estimation peut engendrer des différences importantes dans la comparaison entre alternatives (Dwaikat & Ali, 2018). Pour prévoir ces coûts, il faut estimer les coûts d'exploitation et maintenance, lesquels dépendront des consommations énergétiques et en ressources, et de l'entretien et réparation des installations. Il faut de plus, être en mesure d'anticiper le vieillissement de la construction, de ses équipements, ainsi que la disponibilité des ressources futures qui influenceront sur les stratégies d'entretien et leurs coûts (Plebankiewicz, Leśniak, Vitkova, & Hromadka, 2022).

1.3.4.3.3 Les externalités

Une externalité est définie comme l'impact d'une transaction de marché sur un tiers non impliqué dans cette transaction (Hutchinson, 2017). Elles désignent des coûts ou bénéfices quantifiables issus d'un projet et qui ont des répercussions autres que sur lui-même (ISO 15686-5). Ces externalités peuvent être modélisées en évaluant des coûts de traitements et réparations extérieurs au projet (Preston, 2015). Une externalité peut aussi désigner un impact intangible, telles que les émissions de carbone, qui sont monétisées par la taxe carbone existante dans certains pays (Pelzeter, 2015). D'autres externalités telles que l'esthétique et la qualité de l'environnement de travail, pouvant avoir un impact sur la performance de futurs employés, par exemple, peuvent aussi être incluses dans le calcul (Cole & Sterner, 2000 ; Kishk et al., 2003).

Puisqu'il est possible de monétiser des impacts quantifiables, le coût global étendu se retrouve être une technique complémentaire à l'ACV (Mistry et al., 2016). L'ACV est l'approche permettant d'évaluer les données et impacts d'un produit ou d'un projet dans l'ensemble de son cycle de vie. Pour chaque étape du cycle de vie, sont analysés les éléments d'entrées nécessaires à leur fonctionnement et les éléments de sorties résultants de l'activité. Ainsi, combinée à l'ACG, il est possible de déterminer l'aspect économique de ces impacts environnementaux (Crawford, 2011). D'autres approches peuvent aider à déterminer des

externalités. Le principe d'économie circulaire, par exemple, vise à promouvoir une meilleure et plus longue utilisation de produits et matériaux. Le coût global s'avère être un incitatif pour l'adoption et la compréhension financière de pratiques circulaires, justifiant le choix de composants à réutiliser, étudiant les profits et déterminant les coûts barrières à l'utilisation de stratégies circulaires. (Kambanou & Sakao, 2020 ; Wouterszoon Jansen, van Stijn, Gruis, & van Bortel, 2020). Autre exemple, l'analyse de la valeur est une approche qui vise à atteindre le meilleur équilibre entre économie, efficacité et efficacité à travers des analyses telles que l'analyse coût-bénéfices (Jackson, 2012). Un investissement est considéré comme acceptable si ses avantages sont supérieurs à ses coûts prévus (Saad & Hegazy, 2015). Ce type d'approche est démontré comme complémentaire à l'ACG, alliant la vision systémique de cette dernière et la vision d'optimisation des projets par l'analyse de la valeur (Meng & Harshaw, 2013 ; Swaffield & McDonald, 2008).

1.3.4.4 Point de vue de l'analyse

Les projets de construction sont constitués de multiples parties prenantes qui ont chacune leurs propres attentes vis-à-vis d'un projet. Par conséquent, l'économiste doit être capable d'avoir une vision systémique des coûts du projet. Dans ce contexte, il est intéressant de s'arrêter sur le concept de coût total de possession tel qu'appliqué dans le milieu industriel. Le coût total de possession offre une perspective avantageuse par rapport au coût global, car il se concentre spécifiquement sur les coûts supportés par l'acheteur depuis le moment de l'acquisition, jusqu'à la cession de l'actif (Roda et al., 2020). Ce point de vue centré sur l'acheteur permet des évaluations plus ciblées en fonction de la position de cet acteur dans la chaîne de valeur. Par exemple, Caniato (2014), a développé un modèle de coût total de possession qui prend en compte à la fois les coûts directs et cachés tout au long du cycle de vie de l'actif, tout en considérant les structures de coûts spécifiques pertinents pour chaque partie prenante de la chaîne d'approvisionnement. Hurkens (2006), a proposé un modèle basé sur le coût global intégrant des analyses qualitatives pour évaluer les performances des fournisseurs, permettant ainsi de rendre explicites les conséquences financières des décisions d'achat. En donnant aux fournisseurs accès à ces évaluations, le modèle favorise

l'amélioration continue et encourage le partage des responsabilités. Pearce, Sanford Bernhardt, & Garvin (2010), proposent une perspective plus large du coût global en modélisant le bâtiment comme faisant partie d'un système régi par les interactions entre les utilisateurs, les institutions, les technologies et les contextes environnementaux. Leur modèle applique le coût global à la fois à l'échelle du projet pour comparer les alternatives et identifier les facteurs de coût, mais aussi au niveau du portefeuille pour hiérarchiser les interventions en fonction de la performance des coûts à long terme. Cette prise en compte des différents points de vue peut considérablement améliorer la transparence des coûts et engager une prise de décision collaborative.

1.3.4.5 La gestion des risques

Les premières applications de l'ACG reposaient principalement sur des modèles déterministes, qui ne tenaient pas suffisamment compte des incertitudes liées aux performances des bâtiments ou aux changements de leur environnement au fil du temps (Ammar, Zayed, & Moselhi, 2013). Avec le temps, les techniques d'analyse des risques ont été de plus en plus intégrées afin de tenir compte de ces incertitudes, fournissant ainsi une base plus raisonnée pour la prise de décision et les prévisions financières. Comme indiqué dans la norme ISO 15686-5, le coût global implique des hypothèses sur les conditions futures, ce qui rend essentielle l'identification et la quantification explicites des risques. Si la norme ISO 15686-5 recommande la gestion des risques par le biais de simulations de Monte Carlo et d'analyses de sensibilité, elle ne prescrit pas de méthodologies détaillées pour l'intégration des risques. La littérature fait état d'approches plus structurées. Ainsi, Boussabaine & Kirkham (2004), proposent un cadre en quatre étapes comprenant l'identification des risques, la quantification des risques, les stratégies de réponse aux risques et la surveillance des risques. Ces étapes sont largement acceptées, mais des variations méthodologiques apparaissent en ce qui concerne les approches de quantification des risques. Wang, Chang, & El-Sheikh (2012), utilisent des simulations Monte Carlo combinées à une analyse de sensibilité pour prédire la variabilité des coûts, mais soulignent l'importance de la rigueur afin d'éviter une double comptabilisation des risques, qui peut fausser les évaluations

des coûts. De manière similaire, Ammar et al. (2013), préconisent la méthode de la logique floue comme étant plus adaptées que les simulations Monte Carlo, indiquant que ces dernières reposent sur des données historiques exhaustives, souvent incomplètes ou indisponibles. Les deux méthodes restent cependant toutes deux largement utilisées dans les études sur l'ACG (Azeez, Zayed, & Ammar, 2013 ; K. C. Goh, Goh, & Chong, 2019 ; Jafari, Valentin, & Russell, 2014). Plus récemment, les tendances s'orientent vers des approches numériques telle que l'apprentissage automatique pour améliorer la précision et la fiabilité du coût global (Xinghua Gao, Pishdad-Bozorgi, Shelden, & Hu, 2019).

1.3.5 La mise en œuvre du coût global

L'ACG peut être réalisée à n'importe quelle phase du projet. Cependant, c'est dans les premières phases que les choix ont le plus d'influence sur le projet, il est donc recommandé de réaliser l'analyse le plus tôt possible (Cole & Sterner, 2000). La norme ISO 15686-5 définit les principes du coût global et donne un cadre normatif pour établir les paramètres de calcul. Cependant comme mentionné ci-dessus, il n'existe pas de méthodologie officielle et standardisée pour conduire une ACG (Olubodun et al., 2010). On peut tout de même identifier dans la norme et la littérature les activités à conduire lors d'une analyse de coût global, à savoir : Définir la portée des coûts, déclarer les stratégies et alternatives à évaluer, définir les paramètres de calcul et évaluer les risques (Cole & Sterner, 2000).

1.3.5.1 Définir la portée des coûts

D'après la norme ISO 15686-5, la première étape est de déterminer la portée des coûts, en classant la liste des coûts qui seront inclus dans le calcul, selon les objectifs du projet et les demandes du client. Ce classement des coûts se fait par catégories et permet d'avoir une base de données structurée pour l'analyse. Aussi, la norme présente l'approche comme une méthode d'arbitrage évolutive permettant de mieux prendre en compte l'impact des coûts différés dans les choix d'investissement (MEDDAT, 2009). Elle illustre cette évolutivité en détaillant les éléments à prendre en compte à chaque phase du projet, le niveau de détail étant adapté à la phase en question. Les données peuvent être physiques (ex. surface du bâtiment),

des données d'occupation (ex. nombre de lits, heures d'occupation) ou de performances et de qualité (ex. aspect ou attentes de fonctionnement) (Kishk et al., 2003).

1.3.5.2 Définir la stratégie d'analyse

La norme ISO 15686-5 conseille d'adopter une stratégie d'analyse en amont de sa réalisation, en prévoyant les résultats attendus et la portée de l'analyse. Cette stratégie peut-être une comparaison d'alternatives ou l'évaluation de différents scénarios d'investissements (MEDDAT, 2009; Mistry et al., 2016; Sousa et al., 2018). Il existe plusieurs indicateurs pouvant supporter cette stratégie, tels que la VPN, le coût annuel équivalent, le retour sur investissement, ou encore les économies nettes (Farr & Faber, 2018). La technique la plus utilisée pour effectuer l'estimation des coûts est la VPN, définie comme la somme des flux monétaires qui doit être investie aujourd'hui pour répondre à tous les besoins financiers futurs (Kishk et al., 2003; Pelzeter, 2015). Cet indicateur facilite la modélisation des dépenses et des bénéfices sur une période d'analyse en un seul chiffre, ce qui le rend particulièrement efficace pour la comparaison des conceptions. (Kehily & Underwood, 2017).

1.3.5.3 Définir les paramètres de calcul

Dans la conception, chaque variable peut avoir une incidence sur les coûts du projet, tant à l'investissement qu'en fin de vie (Pelzeter, 2015). Les variables du coût global ont été décrites précédemment en section 1.3.4.

1.3.5.4 Gestion des incertitudes et du risque

Comme vu précédemment, le coût global est une méthode de prévision basée sur des paramètres hypothétiques. Ainsi, il est important de traiter les sources d'incertitudes avant d'appliquer le calcul, en les analysant et si possible, les quantifiant (Pelzeter, 2015). D'après la norme ISO 15686-5, le terme risque est utilisé lorsqu'une probabilité peut être estimée et celui d'incertitude lorsque l'on ne le peut pas. Au début de l'utilisation du coût global, les modèles utilisés étaient principalement de type déterministe, c'est-à-dire qu'ils ne prenaient

pas en compte les changements de comportement possibles des bâtiments et leur environnement (Ammar et al., 2013 ; Wang et al., 2012). Or, l'utilisation d'analyses de risques s'est développée et a été intégrée dans l'ACG pour la compléter (Shattell, 2004).

Deux méthodes sont présentées dans la norme pour quantifier les incertitudes. La première est la méthode Monte Carlo, qui est une analyse basée sur des probabilités. Elle permet de réaliser des simulations d'un système en attribuant des données à des paramètres incertains, pour en prédire les effets à travers une distribution de coûts possibles et leurs probabilités d'apparition (Farr & Faber, 2018). La deuxième est l'analyse de sensibilité, étudiant les impacts de modifications de paramètres indépendants, sur ceux qui sont dépendants (Kishk et al., 2003). Ainsi, cette analyse permet de tester les changements relatifs aux hypothèses de calcul comme le taux d'actualisation ou la période d'analyse et de déterminer les scénarios les plus pessimistes et optimistes (ISO 15686-5 :2017).

1.3.5.5 Le calcul du coût global

Le calcul du coût global est finalement réalisé par l'agrégation des coûts actualisés du cycle de vie du projet, tels qu'ils auront été définis lors de la stratégie d'analyse. Le calcul est représenté par l'équation 1.1 (ISO 15686-5 :2017) :

$$\text{Coût Global} = I_0 + \sum_{t=1}^N \frac{Dt - Rt}{(1+a)^t} - \frac{VN}{(1+a)^N} \quad (1.1)$$

I_0 : montant (ou écart entre 2 options) de l'investissement à l'année 0

Dt : dépenses (ou écart de dépenses entre 2 options) de l'année t

Rt : revenus (ou écart de revenus entre 2 options) de l'année t

VN : valeur (ou écart de valeur) résiduelle

a: taux d'actualisation

N: horizon économique (en années)

1.3.6 La modélisation des informations du bâtiment (BIM)

L'industrie de la construction est un secteur connu pour être très fragmenté, avec des projets uniques, divisés en plusieurs corps d'état, regroupant des acteurs différents, eux-mêmes impliqués dans plusieurs projets (Bertelsen & Sven, 2003). Cette fragmentation affecte l'ensemble des objectifs de projets, tant en termes de qualité, productivité ou rentabilité. Plus encore, c'est un frein important à l'adoption d'innovations et à l'amélioration de ses pratiques. Toutefois, l'émergence d'outils de conception assistée par ordinateur et de modélisation de l'information des bâtiments (BIM) présente un potentiel d'amélioration important pour l'industrie (Crotty, 2011). La littérature montre que l'intégration du BIM a un effet positif sur les étapes de conception et de planification des projets de construction, facilitant le processus décisionnel grâce à sa capacité d'exploitation des données qui permet de générer et évaluer rapidement des conceptions alternatives (Ayman, Alwan, & McIntyre, 2020 ; Barnes, 2019 ; Seyis, 2020).

Considéré comme un accélérateur de changements, ce qu'on appelle le BIM est « *l'ensemble de politiques, de processus et de technologies en interaction qui génère une méthodologie pour gérer les données essentielles d'une conception et d'un projet en format digital tout au long du cycle de vie du bâtiment* » (Succar, 2009). L'adoption du BIM est aujourd'hui conventionnée par des niveaux de maturité, commençant par le niveau 0 pour les plans en 2 dimensions, le niveau 1 pour les modèles 2D ou 3D orientés objets. Le niveau 2 désigne un environnement 3D qui porte sur l'échange entre différents modèles 3D grâce à des outils collaboratifs, et le niveau 3 représente un modèle-serveur collaboratif qui permet l'intégration de données en réseau, pour un partage de données en temps réel à toutes les phases du cycle de vie du projet (Barnes, 2019 ; Georgiadou, 2019).

Le modèle 3D permet de visualiser et parcourir le projet, détecter les conflits ou encore être utilisé pour la préfabrication. L'utilisation de ce modèle 3D peut être approfondie grâce à des logiciels et fonctionnalités complémentaires. Ces logiciels permettent d'utiliser pleinement les fonctionnalités du modèle et ainsi améliorer l'ensemble des processus de conception, et

même de construction. Ces utilisations ont donné lieu aux termes 4D pour des applications utilisant le temps, 5D pour les coûts, 6D et 7D correspondent respectivement à des applications d'analyses énergétiques et de gestion de la maintenance (Barnes, 2019). Ces dernières appellations sont cependant vouées à évoluer, voire disparaître, car il existe beaucoup de divergences sur les correspondances des dimensions 6D et les suivantes.

Le BIM pour l'estimation des coûts présente de nombreuses opportunités qui vont permettre de réduire considérablement les temps de réalisation des tâches et augmenter la fiabilité des résultats (Mitchell, 2012). Ces améliorations arrivent d'abord par l'exploitation du potentiel d'automatisation de l'extraction de quantités d'éléments depuis les modèles numériques (Smith, 2014). Cette automatisation diminue considérablement le temps consacré aux métrés et réduit les erreurs de comptage (Mesároš, Smetanková, & Mandičák, 2019). Les données de coûts seront idéalement directement intégrées dans le modèle ou en liant une base de données de coûts, automatisant l'estimation (Akanbi & Zhang, 2020). Cependant, cette approche reste encore complexe aujourd'hui. On trouvera donc majoritairement des approches semi-automatiques, par la liaison des modèles à des feuilles de calcul pour y actualiser les quantités, puis des prix sont ajoutés manuellement (Su-Ling Fan & Chen-Hua Wu and Chien-Chun Hun, 2015). On retrouve également des approches manuelles où les quantités sont extraites des modèles, puis transférées manuellement vers les feuilles de calcul pour performer l'estimation. De manière générale, le BIM offre malgré tout une meilleure traçabilité des coûts face aux modifications de projet, renforçant ainsi le contrôle financier (Mesároš et al., 2019 ; Smith, 2016).

1.3.7 Les enjeux technologiques du secteur de la construction

Bien que les nouvelles technologies de l'information offrent des possibilités d'amélioration pour les techniques d'estimation, leur intégration optimale dans les processus de projets de construction présente aussi des défis. Parmi les barrières ralentissant l'adoption des nouvelles technologies, nous pouvons faire face à des coûts d'acquisition élevés, une résistance au changement, ou encore un besoin de formation (Azhar, 2011 ; Sahamir, Raja, & Raja, 2021).

Concernant leur mise en œuvre, l'interopérabilité est un des enjeux majeurs du secteur, étant donné sa nature déjà fondamentalement fragmentée. L'interopérabilité est définie comme la capacité de deux ou plusieurs systèmes ou composants à coexister, échanger et utiliser les informations et fonctionnalités qui ont été échangées (Poirier, Forgues, & Staub-French, 2014 ; Succar, 2009).

Afin de promouvoir l'interopérabilité au sein des pratiques industrielles, l'Alliance internationale pour l'interopérabilité, BuildingSMART, a introduit l'openBIM. Cette approche facilite la conception, la réalisation et l'exploitation de projets en s'appuyant sur des normes et des environnements de travail ouverts (Tchouanguem Djuedja, Karray, Foguem, Magniont, & Abanda, 2019). L'openBIM est basé sur les concepts suivants (Jiang, Jiang, Han, Wu, & Wang, 2019b) :

- Gestion des cas d'usage - UCM (Use case Management) : regroupement de cas d'usage BIM répartis tout au long de la chaîne de valeur du projet, qui sont les objectifs BIM. Utilisé pour définir et organiser les fonctionnalités BIM selon les objectifs du projet.
- IFC (Industry Foundation Classes) : schéma de données ouvert utilisé pour représenter, stocker et partager des données. Permet de structurer et échanger les données de modèles exploitables par tout type de logiciel.
- bSDD (BuildingSMART Data Dictionary) : dictionnaire en ligne qui héberge des concepts, les définit, les partage et les relie à d'autres normes ou éléments en dehors de l'IFC. A pour objectif de normaliser les concepts et leurs relations pour assurer un langage commun entre les acteurs.
- Manuel de livraison de l'information - IDM (Information Delivery Manual) : document contenant au moins un cas d'utilisation, une carte de processus et des exigences en matière d'informations. Utilisé pour décrire les processus et exigences d'information pour chaque cas d'usage.
- Format de données ouvert : Format de fichier non-propriétaire. Permet de garantir l'interopérabilité entre logiciels sans dépendance propriétaire.

- API ouverte (Open Application Programming Interface) : Interface qui traduit les requêtes et les informations entre deux applications logicielles. Permet la communication et l'échange de données entre applications.
- Spécifications de livraison de l'information - IDS (Information Delivery Specification) : document regroupant les informations requises pour les actifs dans le modèle. Permet de spécifier les données à fournir, leur contenu et leurs structures attendues.
- BCF (BIM Collaboration Format) : Format de collaboration et de communication. Facilite la coordination et le suivi des échanges entre acteurs dans les maquettes BIM.

Pour assurer un échange fluide des données, la gestion de l'information, joue un rôle important dans la réussite de l'interopérabilité. Récemment, la norme ISO 19650 a été établie pour guider la gestion des données dans les projets de construction. Le suivi de cette norme encourage l'utilisation d'un Environnement de Données Commun, où chaque acteur peut y collaborer en travaillant sur le projet à une même place. Les Environnement de Données Commun offrent de nombreux bénéfices comme la facilité d'échange de données, l'amélioration des prévisions ou encore la numérisation des processus (Çekin & Seyis, 2020). La mise en œuvre de la norme ISO 19650 et la démarche openBIM est démontrée dans l'article de conférence en ANNEXE II. L'approche a montré un potentiel important pour la gestion de l'information et l'interopérabilité dans les projets. Ainsi, cette expérience a grandement influencé la conception de la solution de cette thèse.

1.3.8 Le web sémantique

Une autre avenue pour adresser les problèmes d'interopérabilité est l'utilisation des technologies du web sémantique pour améliorer l'échange d'informations (Sadeghineko & Kumar, 2022). Le web sémantique est une nouvelle forme d'internet structurant et reliant les données entre elles pour qu'elles soient exploitables aussi bien par les humains que les machines (Berners-Lee & Hendler, 2001). Ainsi, l'idée des Données Liées (Linked Data) est

alors apparue, concept visant à relier les données et concepts entre eux afin qu'ils aient un sens (Berners-Lee, 2006 ; Berners-Lee, Hendler, & Lassila, 2001).

Dans ce contexte, chaque domaine de connaissance est représenté par une structure appelée ontologie. Les ontologies sont la représentation de connaissances, et des relations entre elles, à propos d'un concept ou d'un objet dans un langage compréhensible par des machines (Berners-Lee & Hendler, 2001).

Aujourd'hui, les ontologies sont de plus en plus utilisées en industrie et en recherche dans le but de définir un vocabulaire commun pour partager des connaissances et données entre personnes et machines, facilitant la réutilisation du savoir, et son analyse pour l'exploration de nouvelles solutions (Noy & McGuinness, 2001). Ainsi, s'est développé le concept d'ingénierie de l'ontologie. Mizoguchi (2004) donne la définition de l'ingénierie de l'ontologie comme suit :

It is a research methodology which gives us design rationale of a knowledge base, kernel conceptualization of the world of interest, strict definition of basic meanings of basic concepts together with sophisticated theories and technologies enabling accumulation of knowledge which is dispensable for modeling the real world. (Mizoguchi, 2004, p.2).

Le but est de représenter la structure fondamentale des concepts et de fournir tout le vocabulaire nécessaire à la construction d'un modèle. Plus particulièrement, ce concept permet d'offrir un socle sur lequel nous pouvons constituer une base de connaissances partagée (Mizoguchi, 2004 ; Ostrowski, Helfert, & Gama, 2014). Le World Wide Web Consortium (W3C), qui établit des normes et des directives afin de promouvoir le Web sémantique, propose comme structure de représentation normalisée le langage Resource Description Framework (RDF) (Figure 1.1). Le RDF est représenté par un ensemble de triplets, composés des éléments suivants: Le sujet, qui est la ressource que l'on veut représenter, le prédicat, qui est la propriété du sujet, et l'objet, qui est la valeur de cette propriété (Gandon, Krummenacher, Han, & Toma, 2011). Cette structure peut ensuite être

enrichie par l'utilisation de langages apportant des couches de réflexivité et des fonctionnalités supplémentaires, tels que OWL (Web Ontology Language) pour préciser les contraintes de logique entre les concepts, RDFS (RDF Schema) pour préciser et annoter des vocabulaires et hiérarchies de concepts, ou encore SPARQL (SPARQL Protocol and RDF Query Language) pour effectuer des requêtes sur des graphes RDF (Domingue, Fensel, & Hendler, 2011a).

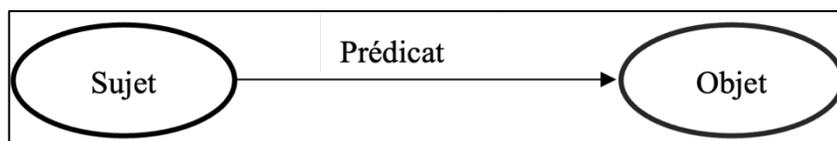


Figure 1.1 Triplets RDF
Adaptée de W3C (2004)

Uschold (1995) définit la construction d'ontologie en quatre étapes : (1) identifier l'objectif, (2) construire l'ontologie (identifier les concepts, les coder et les intégrer), (3) évaluer la pertinence et (4) documenter les hypothèses. L'utilisation d'une ontologie réalisée pour un certain usage, signifie l'intégration de données dans l'ontologie pour les structurer selon l'organisation qu'elle propose. Cette évolution d'une structure de connaissance, à une structure peuplée de données donne lieu à la notion de graphe de connaissances (AL-Aswadi, Chan, & Gan, 2022). Dans l'industrie de la construction, les ontologies permettent notamment l'intégration sémantique des données issues des modèles BIM, pouvant ainsi améliorer les processus d'estimation tels que l'extraction des quantités et l'estimation des coûts (H. Liu, Lu, & Al-Hussein, 2016).

1.4 Énoncé du problème

Le coût global, ainsi que, de manière générale, les approches du cycle de vie, ont été examinés assez longuement dans le milieu académique, et y ont gagné en popularité au début des années 2000. De nombreuses barrières ont été relevées tout au long de ces années, et ce jusqu'à aujourd'hui encore. Cependant, sa pratique dans le monde professionnel est encore peu présente malgré les multiples bénéfices que peut apporter l'ACG. Depuis l'apparition

formelle de l'approche du coût global, les expériences et cas d'application ont peu été partagés et enseignés. Un manque de cas d'application est donc notable dans l'industrie de la construction, résultant en un manque de connaissances et d'outils pour appliquer l'analyse. Aujourd'hui la priorité est donc d'amplifier l'utilisation du coût global en identifiant les leviers d'abord humains, qui encourageront son utilisation, puis technologiques qui permettront de rendre les analyses plus rapides sans renverser radicalement les pratiques actuelles afin d'assurer une intégration et une appropriation progressive et durable.

En explorant la littérature récente, il ressort que la tendance principale est de travailler sur des programmes tentant d'exploiter le BIM pour proposer des solutions logicielles. Ces études sont notamment axées sur l'accès aux données, l'extraction des quantités et la précision des calculs, et des analyses de risques pour renforcer la confiance de l'approche (M. Altaf et al., 2020). Ainsi, il y a un élan, à travers la transition numérique, à ramener le coût global dans les discussions. Plus encore, les technologies du web sémantique apportent de nouveaux procédés innovants, dont le domaine de recherche ne fait que commencer à prendre de l'ampleur. Cependant, les enjeux liés à l'adoption de ces innovations viennent s'entremêler avec les défis d'adoption du coût global. En conséquence, la question d'adoption du coût global dans la pratique ne peut être répondue simplement en apportant davantage de nouvelles solutions techniques sans étudier cet enchevêtrement. Il est nécessaire de comprendre la complexité de l'adoption du coût global dans le contexte de transition numérique du secteur de la construction afin d'apporter une solution qui pourra s'ancrer dans les pratiques.

Le problème énoncé décrit des besoins d'interventions aux niveaux technologique et humain qu'il faut réussir à coordonner afin de proposer une avancée pertinente pour la recherche. La stratégie de recherche à mettre en œuvre nécessite donc une conscience globale de la situation afin de proposer des solutions ciblées démontrant une contribution scientifique et pratique pour l'utilisation du coût global en construction.

1.5 Question de recherche, objectifs et contributions

D'après l'énoncé du problème, nous identifions un besoin de réintégrer une approche ayant un intérêt pour les acteurs de l'industrie. Aussi, nous proposons la question de recherche suivante pour guider notre étude : *Quelles opportunités offrent le contexte socio-technologique actuel des projets de construction pour adopter le coût global dans les pratiques d'estimation ?* L'objectif de cette thèse est d'explorer l'utilisation des technologies sémantiques et du BIM comme outils pour soutenir l'intégration systématique du coût global dans les pratiques d'estimation.

Le problème énoncé décrit une problématique complexe, nécessitant une exploration du sujet sur plusieurs aspects. Au niveau technologique, il y a un besoin d'élargir la recherche sur des solutions informatiques innovantes afin de proposer de nouvelles solutions qui vont plus loin que de simples ajouts de fonctionnalités sur des logiciels BIM. Nous proposons ici d'investiguer le potentiel des technologies sémantiques pour l'approche du coût global. Pour aller chercher ces résultats, un premier sous-objectif est le développement d'une approche dynamique du coût global compatible avec le BIM et basée sur les technologies sémantiques. Pour atteindre ce sous-objectif, deux étapes sont nécessaires : la création d'une ontologie et son instanciation. La première contribution issue de ce sous-objectif est la proposition d'une ontologie du coût global. Ce modèle sémantique est la représentation formelle et informatique de ce domaine de connaissance, permettant à tout utilisateur d'interroger l'agent informatique qui exploite l'ontologie pour réaliser des analyses. De plus, l'ontologie est un artefact flexible et extensible, permettant d'ajouter de nouveaux concepts, s'adaptant ainsi pour répondre aux besoins de chaque utilisateur. La seconde contribution, à travers l'instanciation de l'ontologie, est une solution informatique permettant de faire des analyses du coût global à partir de modèles BIM et des estimations qui l'accompagnent. L'utilisateur peut donc lier ses estimations afin de les interpréter dans une perspective du cycle de vie du projet. Pour finir, la troisième contribution en répondant à ce sous-objectif est de déterminer les bénéfices des technologies sémantiques pour le coût global. Celles-ci permettent notamment l'agrégation de données hétérogènes, le calcul des résultats de manière

automatique, mais surtout l'exploration de ces résultats et la découverte de nouvelles perspectives.

Le second sous-objectif vise à comprendre les mécanismes des projets au niveau humain, afin d'identifier des leviers qui faciliteront l'adoption du coût global. L'atteinte de ce sous-objectif permettra d'identifier les raisons profondes pour lesquelles le coût global n'est pas systématiquement intégré dans la gestion des projets. Pour cela, une enquête auprès des professionnels en estimation a été réalisée. Les contributions sont dans un premier temps une proposition de repositionner comme utilisateur principal de l'ACG, les principaux concernés des analyses économiques des projets, à savoir les estimateurs et économistes mêmes. En effet, la plupart des études intègrent généralement l'ensemble des acteurs du projet, en homogénéisant l'ensemble des perspectives et tirant des conclusions générales. Mais bien que tout le monde puisse bénéficier des interprétations du coût global, la réalisation de cette analyse financière est supposément menée par des experts en coûts. La focalisation sur ces derniers permet donc d'identifier leurs propres défis à l'utilisation de l'approche qui a le potentiel d'apporter une plus-value supplémentaire à ce métier. Finalement, la seconde contribution est la proposition d'un cadre d'intégration organisationnel du coût global, repositionnant ces experts en coûts au centre de la réalisation, et surtout de l'interprétation, de l'ACG pour supporter les décisions.

De manière générale, l'ensemble de la thèse permet d'articuler les réponses à ces objectifs pour proposer une solution intégrée, à la fois conceptuelle et opérationnelle, au problème persistant d'adoption du coût global. En combinant une approche technologique à une compréhension approfondie des pratiques professionnelles, la recherche développe un artefact qui met en perspective le développement d'une pratique répondant aux besoins des estimateurs et des économistes. Cette approche dynamique du coût global s'appuie sur les capacités de l'ontologie, tout en contribuant à la théorie en proposant un cadre de connaissances du coût global flexible grâce à cette même ontologie.

1.6 Approche de la recherche

Cherchant à résoudre un problème pratique, ce projet de recherche s'inscrit dans le cadre d'une recherche appliquée, impliquant le traitement d'enjeux au niveau pratique, méthodologique ou politique, présupposant des faits concrets (Brent & Leedy, 1990). L'objectif de ce type de recherche est de générer de la connaissance pour atteindre un objectif spécifique et pratique (Roll-Hansen, 2017). Pour correspondre à cette vision, la recherche a été menée suivant le paradigme de la science de la conception. Ce paradigme diffère des sciences traditionnelles dans le sens où l'objectif de création de connaissances n'est pas la découverte de lois universelles, mais plutôt de proposer une solution pratique et de faire état de la connaissance générée par les processus de création de la solution en question (Dresch, Lacerda, & Antunes Jr, 2015a). Notre recherche se veut à comprendre comment les technologies sémantiques peuvent servir à développer un outil adéquat pour le coût global, et d'évaluer si cet outil correspond aux exigences qui seront définies, ce qui s'accorde donc avec la science de la conception. Une méthodologie de Recherche en Science de la Conception (RSC) a donc été développée. Le cœur de cette recherche étant la proposition d'une ontologie, l'approche de cette thèse a été adaptée et inspirée de deux cadres de recherches existants. Le premier, est le cadre fondamental proposé par Hevner (2007), représentant trois cycles :

- Le « Cycle de pertinence » : Ce cycle désigne l'étude du domaine d'application de la RSC. Il permet de relier la recherche avec son domaine d'application en déterminant les besoins pour le secteur, mais aussi la pertinence des artefacts qui seront conçus dans le cadre de leur évaluation.
- Le « Cycle de conception » : Ce cycle désigne le centre des activités de la recherche, il consiste en la conception des artefacts et en leur évaluation.
- Le « Cycle de rigueur » : Ce cycle désigne la mise en relation de la recherche avec les connaissances, théories et artefacts actuels. Le but est de garantir l'innovation et la contribution à la recherche. Le chercheur doit s'assurer de la pertinence des méthodes et théories sur lesquelles il s'appuie pour construire son artefact.

Le deuxième cadre est celui présenté par Nguyen, Gardner, & Sheridan (2019), proposant une méthodologie de la RSC adaptée pour la création d'ontologies. Son cadre reprend les mêmes cycles du premier cadre, mais les spécifie. Le cadre ontologique précise le domaine d'application avec la prise en compte des ontologies existantes, des vocabulaires formels, et des modèles de connaissance réutilisables. De même, le cycle de pertinence met en relation les besoins pratiques avec des concepts et relations formels qui relient la future ontologie. Enfin, le cycle de conception, toujours central, conserve sa fonction de construction et d'évaluation d'un artefact, mais est inévitablement la construction d'une ontologie.

Les deux cadres évoqués sont pertinents pour la direction de cette recherche. Toutefois, le premier cadre d'Hevner n'a pas été spécifiquement conçu pour la construction d'ontologies, et celui de Nguyen nécessite encore une validation pratique approfondie. Nous proposons d'articuler ces derniers afin de suivre un cadre consolidé qui pourra s'appliquer au contexte de la recherche. L'approche de recherche retenue est présentée dans la Figure 1.2.

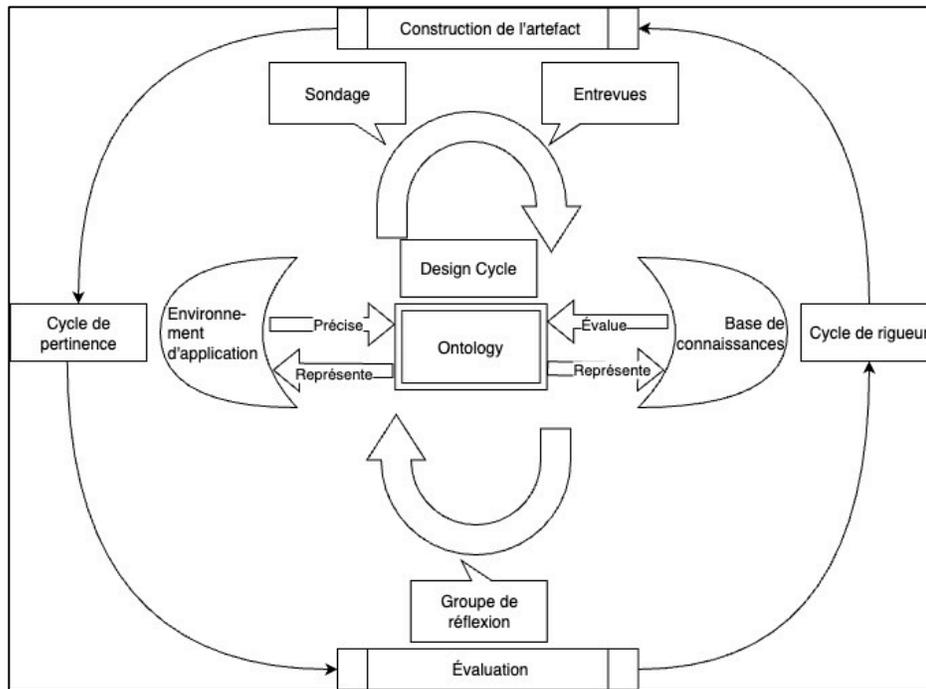


Figure 1.2 Cadre de la recherche basée sur la Science de la Conception
Adaptée de Hevner (2007) et Nguyen (2019)

Dans cette recherche, la science de la conception est considérée non pas comme une simple méthodologie, mais comme une perspective de recherche complète, disposant de sa propre ontologie, épistémologie et méthodologie. La posture ontologique du paradigme de la science de la conception admet des états du monde multiples, spécialement du à son caractère itératif, mais il se distingue de la posture interprétiviste qui admet des réalités multiples (Vaishnavi & Kuechler, 2015). Ainsi, nous considérons une réalité unique, mais dans laquelle chaque contexte d'application engendre un état du monde différent qui est façonné par des contraintes et des interactions socio-techniques (Vaishnavi & Kuechler, 2015).

1.6.1 Le pragmatisme comme posture épistémologique

Le pragmatisme est un paradigme de recherche apparu vers la fin du 19^{ème} siècle, se démarquant par une posture non-fondamentaliste, considérant l'utilité de la connaissance selon ses effets pratiques dans un contexte donné, plutôt que de sa représentativité absolue de

la réalité (Gillespie, Glăveanu, & De Saint Laurent, 2024). Gillespie (2024) décrit huit préceptes du pragmatisme qui en illustrent la philosophie (Tableau 1.2).

Tableau 1.2 Les principes de la posture pragmatiste

Principes énoncés par Gillespie (2024)	Explication des principes tirées de Gillespie (2024)
1) « La vérité réside dans les conséquences »	Le pragmatisme repose sur la compréhension des phénomènes à travers leurs conséquences pratiques. Il ne cherche pas à établir une hiérarchie entre des perspectives, mais à en évaluer leurs effets pratiques. Le but n'est pas d'accepter une connaissance, mais de la comprendre dans son contexte.
2) « Les théories sont des théories pour l'action »	D'un point de vue pragmatiste, la valeur d'une idée dépend de son utilité concrète. Une bonne théorie permet une action sur un objet avec un minimum d'imprévu.
3) « La recherche sert davantage à créer des questions qu'à répondre à des questions »	L'approche pragmatiste apporte une théorisation non pas définitive mais en faisant émerger de nouveaux problèmes et questions pertinentes avec l'évolution du contexte.
4) « Les données sont toujours flexibles »	Les données sont interprétées selon le problème posé et le contexte. Leur sens est construit et évolutif, reflétant une réalité correspondant à la perspective adoptée et la progression de la recherche et du contexte.
5) « Les méthodologies qualitatives et quantitatives sont synergiques »	Les approches qualitatives et quantitatives sont vues comme complémentaires. Le pragmatisme valorise l'utilisation combinée des méthodes pour mieux comprendre un phénomène, en tirant parti des forces de chacune.
6) « La recherche sociale crée à la fois du pouvoir et des responsabilités. »	Dans une posture pragmatiste, la recherche a des conséquences sur la pratique. Ceci implique une responsabilité de la part du chercheur de proposer une théorie adaptée aux acteurs du terrain, sans les déposséder de leurs actions.
7) « La recherche sociale devrait viser à élargir les possibilités humaines. »	Les résultats pragmatistes doivent permettre d'agir sur le monde de manière plus juste et mieux adaptée au contexte. Ainsi, une recherche est utile si elle ouvre de nouvelles possibilités pour les acteurs, en renforçant leur pouvoir d'agir dans leur contexte.

La posture épistémologique de la science de la conception repose sur l'idée que la connaissance se construit à travers le processus de conception, dans un contexte donné et sous contraintes réelles (Vaishnavi & Kuechler, 2015). Cela correspond au pragmatisme avançant la construction de la connaissance dans l'action (Gillespie et al., 2024). Cependant nous estimons que le pragmatisme permet d'en prolonger la portée réflexive, en soutenant que la validité de cette connaissance dépend de ses conséquences pratiques et de sa capacité à transformer le contexte étudié.

Le pragmatisme conserve l'avantage de la flexibilité d'utilisation de méthodes mixtes (Onwuegbuzie & Leech, 2005). Ce paradigme de recherche ne restreint pas les choix méthodologiques du projet, tant qu'ils restent adaptés au problème de recherche, avec une posture ouverte à l'analyse croisée des données qualitatives et quantitatives (Kaushik & Walsh, 2019 ; Onwuegbuzie & Leech, 2005). Plus encore, ce paradigme encourage la co-construction des problèmes avec les acteurs de terrain, afin de construire des solutions contextualisées afin de contribuer à la transformation des pratiques (Morana, 2003a). Aussi, ce choix impliquera que l'ontologie créée suive les principes du pragmatisme, orientant les connaissances modélisées vers une utilité concrète, l'interopérabilité et l'application à des situations réelles (Kolchin et al., 2015).

Il ne va pas sans dire que le pragmatisme reste tout de même une posture imparfaite ayant ses propres limites. Premièrement, son orientation prononcée vers la pratique peut limiter la validité scientifique, entraînant un risque de manque de rigueur et de conflits d'intérêts (Morana, 2003a). Cette focalisation sur l'utilité immédiate, dans un contexte limité, pourrait aussi conduire à ignorer des questions plus larges qui ont aussi une influence sur le contexte local (Gillespie et al., 2024 ; Morana, 2003a). De plus, l'approche pragmatique est parfois jugée d'un manque de critique vis-à-vis des résultats, estimant qu'un chercheur peut être facilement influencé par les objectifs pratiques locaux, produisant des connaissances sans recul sur la situation (Gillespie et al., 2024).

Face aux différentes critiques adressées au pragmatisme, notre choix méthodologique de la RSC nous semble tout de même approprié, car cette approche incarne précisément les principes pragmatiques tout en répondant aux limites soulevées précédemment. Comme l'indique clairement Hevner (2007), la RSC est ancrée dans une vision pragmatique, mais elle ne se réduit pas à la seule utilité immédiate des résultats produits. En effet, selon Hevner (2007):

Pragmatism is a school of thought that considers practical consequences or real effects to be vital components of both meaning and truth. Along these lines I contend that design science research is essentially pragmatic in nature due to its emphasis on relevance; making a clear contribution into the application environment. However, practical utility alone does not define good design science research. It is the synergy between relevance and rigor and the contributions along both the relevance cycle and the rigor cycle that define good design science research. (Hevner, 2007, p.91)

Dans cette recherche, une attention particulière sera donc portée à cette exigence de rigueur, en veillant à ce que l'utilité de l'artefact soit tout aussi importante que les connaissances produites pour sa conception et ses effets sur le contexte étudié. La considération de la science de la conception comme paradigme à part entière, avec une posture ontologique qui lui est propre complémente cette posture épistémologique. En effet, la posture de la science de la conception convient que plusieurs solutions peuvent coexister et être également valides, chacune adaptée à un environnement spécifique. Le chercheur, en tant qu'acteur de conception, participe lui-même à la construction de ces états du monde. Cela signifie qu'une autre personne, placée dans des conditions similaires, pourrait concevoir un artefact différent mais tout aussi cohérent. Cette posture reconnaît donc que la valeur d'une recherche en science de la conception ne réside pas uniquement dans l'artefact produit, mais aussi dans la compréhension théorique du processus qui a permis son émergence. La théorie devient alors un résultat essentiel, car elle rend transférable la connaissance issue d'un état du monde particulier vers d'autres contextes.

1.6.2 La méthodologie de recherche en science de la conception

La science de la conception ambitionne la création d'artefacts pour résoudre des problèmes pratiques. Ces artefacts, se présentent sous la forme de concepts, de modèles, de méthodes ou d'instanciations, et peuvent également inclure des innovations sociales ou de nouvelles ressources techniques, organisationnelles ou informationnelles (De Sordi, 2021 ; Peffers, Tuunanen, Rothenberger, & Chatterjee, 2007). Un artefact est défini comme un élément créé par l'homme, permettant de traiter un certain type de problème (Dresch et al., 2015a ; Offermann, Levina, Schönherr, & Bub, 2009 ; Winter, 2008). L'artefact résultant a pour objectif de trouver une solution satisfaisante à un problème pratique, de décrire « comment les choses devraient être » et être généralisable à une classe de problèmes (Dresch, 2015). Pour répondre aux critères d'une recherche valide, la mise en œuvre de la RSC nécessite l'application d'un processus qui assure l'évaluation de l'artefact produit, et générant des connaissances qui seront ensuite communiquées et contribueront à la recherche (Peffers et al., 2007). Les contributions des recherches peuvent répondre à un paradigme axé sur les sciences comportementales, se concentrant sur les connaissances propositionnelles (descriptives et explicatives) améliorant la compréhension de phénomènes tels que l'impact des technologies. Elles peuvent aussi être axées sur la pratique mettant l'accent seulement sur les connaissances applicables (prescriptives) (Gregor & Hevner, 2013b). Basées sur les cadres méthodologiques de Dresch (2015) et Nguyen (2019), nous avons déterminé des étapes clés à suivre tout au long du projet afin de mener à bien la méthodologie choisie. Les étapes sont décrites dans le Tableau 1.3.

Tableau 1.3 Étapes de la recherche en Science de la Conception
(Dresch et al., 2015a ; Nguyen et al., 2019)

Étape 1 : Définition du problème	Cette étape sert à identifier clairement et formellement le problème dans le contexte de l'étude. L'étape va permettre de définir les enjeux pratiques et théoriques du problème, ainsi que les besoins spécifiques auxquels l'artefact devra répondre.
Étape 2 : Exploration du problème	Cette seconde étape vise à définir la portée de la recherche et ses objectifs. Nous considérons ici la prise de conscience du problème et l'identification des solutions existantes. Cette étape comprend finalement, la définition des questions de recherche ainsi que la proposition des objectifs pour les adresser.
Étape 3 : Exigences de conception de l'artefact	La troisième étape est l'investigation et l'évaluation des exigences de conception pour l'artefact. Ces exigences seront déterminées par une revue de littérature et l'exploration des pratiques du contexte étudié.
Étape 4 : Conception de l'artefact	L'étape de conception débute par l'identification de solutions existantes et alternatives afin de proposer une conception innovante.
Étape 5 : Évaluation Ex-Ante	Cette étape finalise la phase de conception de l'artefact. Les activités d'évaluation ont pour objectif d'évaluer la faisabilité de l'artefact, les choix de conception et à identifier les contraintes de mise en œuvre.
Étape 6 : Développement de l'artefact	Cette étape concerne le développement de l'artefact suivant des spécifications définies.
Étape 7 : Évaluation de l'artefact	Pour finir le développement, une évaluation de l'artefact est requise afin de juger de sa performance, son adéquation avec les besoins et objectifs et la résolution du problème identifié.
Étape 8 : Communication des résultats	Cette étape finale sert à assurer la formalisation et communication d'une conclusion de la recherche sur les résultats. Les activités doivent permettre la généralisation de l'artefact à sa classe de problème.

Les étapes décrites suivent un processus logique commençant par l'analyse d'une situation donnée, suivie d'une projection vers la future situation envisagée et d'une formalisation et synthèse de cette nouvelle situation (Hugentobler & Jonas, 2004). Ces phases s'accordent avec les différents raisonnements utilisés dans la RSC, à savoir : la déduction, l'induction et l'abduction (Dresch et al., 2015a ; Pries-Heje, Baskerville, & Venable, 2011). Le raisonnement par déduction permet de tirer des conclusions à partir de prémisses. Le raisonnement par induction permet de tirer des conclusions à partir d'observations. Et le

raisonnement par abduction a pour objectif de trouver une condition à une conclusion (Pries-Heje et al., 2011). La RSC est une méthode de recherche qui s'appuie donc sur la compréhension d'un environnement et de ses enjeux afin de construire des artefacts qui répondront directement à ces problèmes (Dresch et al., 2015a).

Afin de garantir la validité de la recherche, plusieurs méthodes existent, et le choix dépendra du type d'artefact créé. D'après Hevner (2004), il est possible de réaliser une évaluation observationnelle à travers une études de cas de l'artefact dans son environnement ou une étude de terrain lorsque plusieurs projets sont disponibles. Ensuite, l'évaluation analytique évalue la structure de l'artefact, son architecture, ses propriétés et ses interactions. L'analyse expérimentale étudie le fonctionnement de l'artefact. L'évaluation par tests à travers des essais repère les erreurs et défauts de l'artefact. Finalement, l'évaluation descriptive contextualise l'artefact avec les théories actuelles pour identifier son utilité (A. R. Hevner, March, Park, & Ram, 2004). Venable (2012) classe les méthodes de recherche selon leur nature, et le moment de leur évaluation. Ainsi, les méthodes d'évaluation peuvent être « naturelles », c.-à-d. réalisées dans l'environnement auquel l'artefact est destiné, ou « artificielles », c.-à-d. réalisées dans un environnement contrôlé et/ou simulé (Venable, Pries-Heje, & Baskerville, 2012). Par la suite, les méthodes d'évaluation peuvent être mises en œuvre « ex-ante », avant que l'artefact final ne soit implémenté, ou « ex-post », une fois que l'artefact est opérationnel (Pries-Heje, Baskerville, & Venable, 2008).

Sonnenberg (2012) propose un processus de quatre rondes d'évaluations réalisées après chaque étape du projet pour assurer la validité de la recherche (Figure 1.3). Les évaluations avant la construction de l'artefact seront Ex Ante et celles d'après la construction Ex Post. Chaque évaluation permet de faire un retour à l'étape précédente afin de la compléter et de passer rigoureusement à la suite du projet.

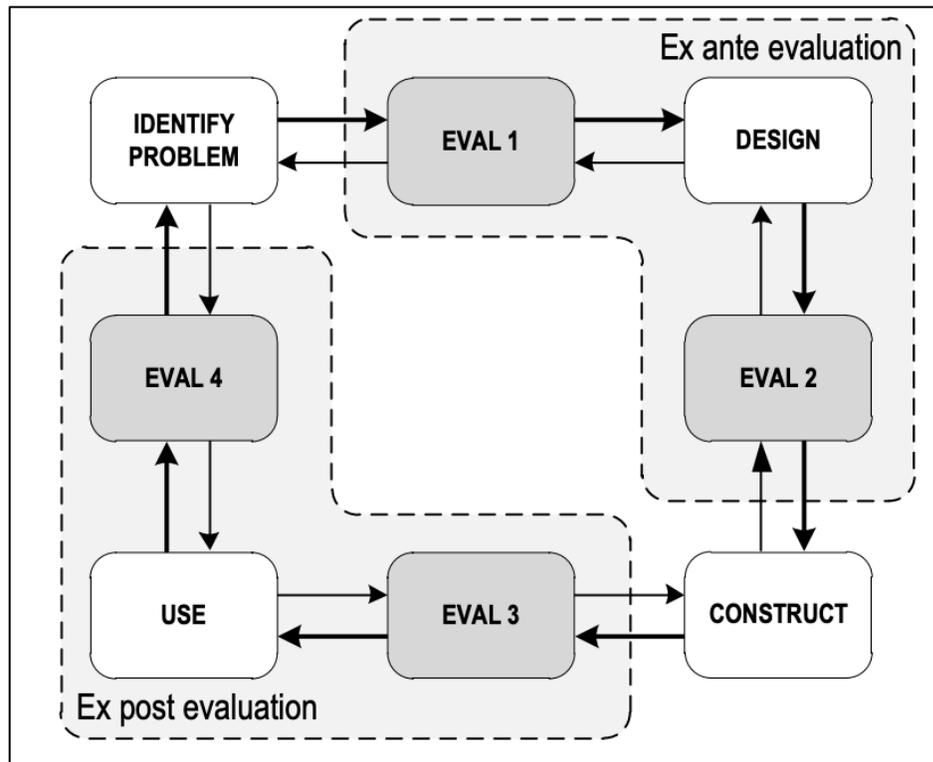


Figure 1.3 Schéma d'évaluation pour les artefacts en Science de la Conception.

Tirée de (Sonnenberg & vom Brocke, 2012).

La RSC est une méthode de recherche relativement récente et le concept de validité associé est encore discuté aujourd'hui (Recker, 2021). Recker (2021), indique que le plus important est de démontrer l'utilité de l'artefact, impliquant qu'il soit innovant, ait un impact positif par rapport à un autre artefact similaire et qu'une évaluation prouve cette utilité (Recker, 2021).

Larsen (2020) a identifié et défini 10 groupes de validité applicables à la RSC :

Tableau 1.4 Critères de validité de la SDC

Critères de validité (K. Larsen et al., 2020)	Définitions
1- Congruence	Fidélité d'instanciation avec les principes de conception et les théories (K. Larsen et al., 2020). Ce critère permet d'évaluer la cohérence de l'artefact avec la recherche menée.
2- Critères de validation	Validation de l'accordance des résultats de l'artefact avec les objectifs (K. Larsen et al., 2020). Ce critère évalue la conformité de l'artefact avec les objectifs de la recherche.
3- Critères mesurés	La mesure de la conformité de l'artefact avec les objectifs (K. Larsen et al., 2020). Ce critère repose sur l'établissement de mesures de la conformité de l'artefact avec les objectifs de la recherche.
4- Données d'entrée	Les données d'entrée sont adaptées à l'artefact (K. Larsen et al., 2020). Ce critère porte sur l'évaluation des données qui sont visées et utilisées pour l'utilisation de l'artefact.
5- Validation interne de l'artefact	Les composants internes de l'artefact sont transparents, cohérents et explicables (K. Larsen et al., 2020). Ce critère vise à l'évaluation de chaque élément constituant l'artefact.
6- Langage	Utilisation d'un langage approprié pour la description et composition de l'artefact (K. Larsen et al., 2020). Ce critère évalue la cohérence et la rigueur sémantique utilisée pour construire et décrire l'artefact.
7- Amélioration relative	Améliorations d'un artefact par rapport à un autre similaire (K. Larsen et al., 2020). Ce critère compare l'artefact avec un artefact similaire pour évaluer sa contribution relative.
8- Représentativité	Fidélité de l'artefact dans la représentation de la réalité (K. Larsen et al., 2020). Ce critère évalue la pertinence et l'applicabilité de l'artefact pour son domaine d'applicabilité.
9- Exigences	Satisfaction de l'artefact avec les besoins physiques et fonctionnels (K. Larsen et al., 2020). Ce critère évalue la correspondance de l'artefact avec les exigences nécessaires à son applicabilité.
10- Théories	Justification de la théorie proposée, sa formulation et son ancrage avec la pratique (K. Larsen et al., 2020). Ce critère évalue la pertinence de la théorie amenée dans une recherche et sa capacité à répondre aux besoins du terrain.

1.7 Application de la méthodologie

La conduite de cette recherche s'est concentrée sur la construction progressive d'une solution adaptée tant pour la pratique que la théorie, en tirant des leçons de données collectées qualitativement et quantitativement, tout en se référant à la littérature. Cette approche s'ancre ainsi dans le pragmatisme, utilisant les résultats des investigations pour produire des connaissances utiles et contextualisées (Kelly & Cordeiro, 2020). La démarche abductive utilisée a permis, par l'observation des problèmes concrets observés sur le terrain, d'enrichir l'artefact par itérations. L'artefact proposé a donc été développé tout au long du projet en réponse aux données empiriques et aux rétroactions reçues à chaque étape. La philosophie utilisée permet à l'ontologie proposée de rester ouverte pour de futurs travaux, assumant qu'elle n'est pas une représentation statique, mais évolutive. Le processus de recherche est illustré dans la Figure 1.4.

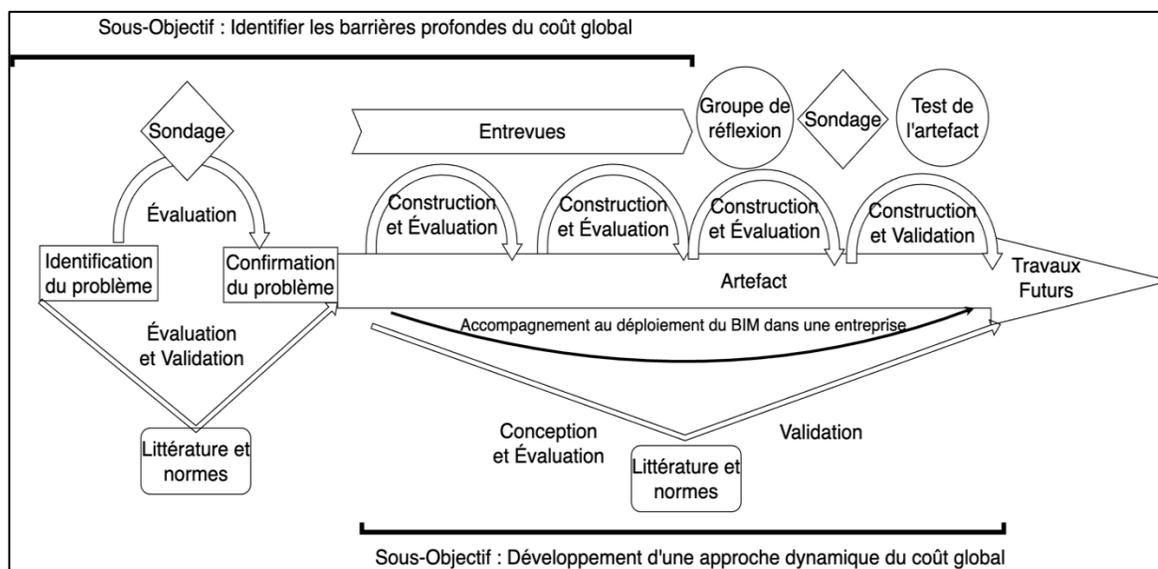


Figure 1.4 Processus de recherche adoptée par la thèse

1.7.1 Collecte de données

Une approche de collecte de données mixte a été engagée tout au long de ce projet, suivant la position du pragmatisme qui soutient l'utilisation de méthodes qualitatives et quantitatives pour renforcer la richesse des résultats de la recherche.

1.7.1.1 Collecte de données quantitatives

La collecte des données quantitatives s'est déroulée en deux temps à travers des sondages complémentaires. Le premier sondage visait à dresser un portrait initial de l'état des connaissances et des pratiques du coût global chez les économistes de la construction et les estimateurs au Québec. Administré en ligne par l'intermédiaire de l'Association des Estimateurs et Économistes du Québec (AEÉCQ), le sondage a recueilli 21 réponses. Il interrogeait notamment l'expérience des participants avec le coût global, le contexte éventuel d'utilisation ou de non-utilisation de l'approche, ainsi que la perception sur le potentiel du coût global à améliorer les investissements en construction et à valoriser le rôle des estimateurs.

Un deuxième sondage, en temps réel, a permis de confirmer et d'approfondir les résultats du premier, tout en élargissant la portée à une audience plus vaste. Ce sondage a été mené lors d'un congrès technique de l'AEÉCQ et comptait 50 répondants, représentant une part significative des participants présents à l'événement. Ce deuxième questionnaire abordait davantage les perspectives d'adoption concrètes du coût global dans la pratique professionnelle, identifiant notamment les défis principaux liés à son intégration et évaluant la fragmentation actuelle des informations nécessaires entre systèmes et parties prenantes.

1.7.1.2 Collecte de données qualitatives

La collecte des données qualitatives a reposé sur plusieurs démarches complémentaires. D'abord, des entretiens semi-structurés ont été menés auprès de 15 experts dans l'estimation des coûts issus des secteurs public, privé et de la recherche, incluant des estimateurs,

économistes, analystes environnementaux et professeurs. Ces entretiens visaient à explorer leur compréhension du coût global, les limites perçues de son application actuelle, les conditions favorables à son adoption, et les perspectives de l'intégration de l'aspect de durabilité dans l'estimation des coûts. Les entretiens ont été réalisés sur une période de 8 mois, permettant une analyse progressive et des discussions orientées jusqu'à la révélation de schémas récurrents dans les discours, suggérant une saturation des thèmes explorés.

Ensuite, un groupe de discussion réunissant cinq professionnels expérimentés en coût global a été mis en place. Cette démarche visait dans un premier temps à recueillir des réflexions sur l'ontologie du coût global et son contenu, et dans un même temps de définir les besoins fonctionnels et les spécifications d'une plateforme fondée sur l'ontologie.

En complément de ces démarches, une mission d'accompagnement au déploiement du BIM dans le département d'estimation de la Société Québécoise des Infrastructures (SQI) a été menée durant trois ans. Cette expérience a permis de mieux comprendre le contexte industriel dans lequel cette recherche se situe, permettant de témoigner des enjeux technologiques, procéduraux, organisationnels et humains quant à l'intégration du BIM, et spécifiquement pour l'usage de l'estimation.

1.7.2 Analyse des données et construction de l'artefact

L'analyse des données qualitatives et quantitatives a été menée par une approche d'analyse comparative constante et soutenue par raisonnement abductif. La première enquête a consisté en un sondage ciblant un groupe de professionnels experts en estimation des coûts, et a servi d'étape exploratoire pour identifier les principaux obstacles à l'adoption du coût global. Il s'agissait notamment du manque de connaissances et de temps, de l'absence de demande de la part des clients, la difficulté d'accès aux données et de l'insuffisance d'outils adaptés. Cette enquête a permis d'établir un point de départ pour la recherche et d'élaborer les questions d'entretiens semi-dirigés pour explorer plus en profondeur les résultats.

Les entretiens ont été transcrits et examinés à l'aide du logiciel d'analyse NVivo grâce auquel plusieurs cycles de codage ont été réalisés. Afin d'assurer une compréhension approfondie des témoignages recueillis, trois cycles de codage ont été réalisés. Le codage initial était de type « in vivo », et a permis d'extraire les expressions exactes des participants afin d'en interpréter les obstacles perçus à l'application du coût global. Le second codage était axial, et a servi à préciser et à structurer en catégories les difficultés pratiques rencontrées lors de la mise en œuvre du coût global. La troisième itération a été réalisée par un codage par motifs (pattern coding), et a permis d'analyser les facteurs de réussite dans les témoignages où le coût global a été mené avec succès.

Les codages ont été réalisés de manière progressive à mesure que les entrevues ont été procédées. Puis, une analyse comparative constante a permis de croiser l'ensemble des données, qualitatives et quantitatives, lors de chaque cycle. En somme, l'analyse a été complétée par la réalisation du deuxième sondage qui a permis une triangulation des données, comparant ces nouveaux résultats avec les perspectives tirées. Cette analyse a permis de finaliser une première étape répondant au 2^{ème} sous-objectif en proposant un cadre d'intégration organisationnel du coût global, positionnant au centre, les experts en coûts.

Dans un même temps, l'ontologie du coût global a été construite de manière progressive, soutenue par les données collectées et l'accompagnement de l'entreprise, qui ont permis de formuler les exigences de l'artefact. Une première ontologie a été réalisée simplement à partir de la norme ISO 15686-5 afin d'établir un cadre ontologique de connaissance de base. Ce cadre ontologique a finalement été complété à la fin de l'analyse des entrevues pour enrichir sa logique grâce aux conclusions tirées des entrevues, et intégrant la fonctionnalité de calcul automatique. À la suite de cette conception, un groupe de réflexion a été mené afin d'établir une validation ex-ante de l'artefact, fondé sur cette même ontologie. L'ontologie de calcul et ses fonctionnalités d'agrégation automatique des données hétérogènes a été présentée au groupe de réflexion. Cette rencontre a permis la validation de la conception de l'artefact et du contenu de l'ontologie. Pour terminer, la construction de l'artefact a été entreprise, puis validée par un test avec deux projets réels, permettant de valider les bénéfices

apportés par une solution ontologique. L'ensemble du processus de construction est présenté dans la Figure 1.5.

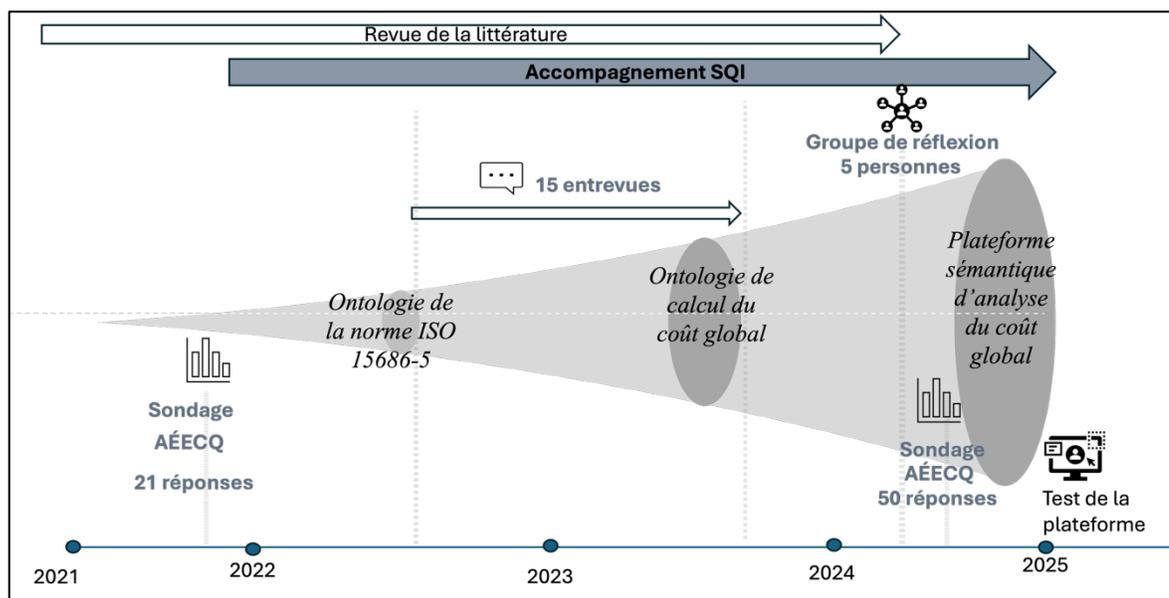


Figure 1.5 Processus de construction de l'artefact

Il convient de noter que la taille des échantillons demeure limitée et qu'ils reflètent principalement le contexte québécois. Ce constat ne constitue pas uniquement une limite méthodologique, mais traduit également la réalité d'un manque d'expertise et de pratique du coût global dans ce contexte, renforçant la pertinence de cette recherche. Afin de combler cette limite, la recherche a triangulé différentes sources de données (sondages, entretiens et groupe de réflexions) et s'est appuyée sur la littérature scientifique existante permettant de confronter les perspectives et d'assurer une analyse complète.

1.8 Structure de la thèse

La présente thèse est composée des trois articles, qui sont des chapitres à part entière, et dont les résultats et discussions mènent à l'atteinte de l'objectif de ce projet de recherche. Deux articles de conférence seront présentés en annexes I et II, qui serviront à supporter la compréhension du contexte de la recherche. L'ensemble des articles seront alors mis en

relation dans une discussion sur les résultats de chaque article afin de démontrer l'atteinte de l'objectif principal de l'étude.

1.8.1 Article 01 – Accelerating the use of Whole Life Costing in construction projects: a new role for cost engineers

L'article 01 présente et discute l'élaboration d'un cadre soutenant l'intégration du coût global dans l'organisation des projets de construction. Sur la base de données qualitatives et quantitatives recueillies auprès d'experts financiers du bâtiment, l'article tente de proposer une solution organisationnelle face aux défis rencontrés pour l'adoption du coût global. L'étude utilise la méthode de la Théorie Ancrée et sa technique d'Analyse Comparative Constante pour identifier ces facteurs contextuels qui favorisent l'utilisation de l'approche.

L'article 01 contribue par l'apport de connaissances propositionnelles, confirmant les barrières du coût global mais aussi en ouvrant le débat sur la prise de responsabilité de mener l'ACG. Le cadre propose que ce rôle soit pris par les professionnels des coûts de construction. L'article 01 contribue à ce projet de thèse en clarifiant comment le coût global peut s'implanter durablement dans les pratiques, et surtout, positionne l'utilisateur final de l'artefact.

1.8.2 Article 02 – A Core Ontology for Whole Life Costing in Construction Projects

L'article 02 propose une étude pour la création d'une ontologie fondamentale et standard de l'ACG. Sur la base de la norme ISO 15686-5:2017, donnant des lignes directrices pour l'application du coût global, et appuyé par les besoins techniques exprimés par un groupe de réflexion, le modèle sémantique a été créé suivant la méthode proposée par Nguyen (2019), c-à-d. la Recherche en Science de la Conception Ontologique. Cette méthodologie axée sur la création d'une ontologie a permis d'assurer sa qualité tant sur le plan pratique que théorique. Pour compléter cette méthodologie, l'ontologie a été construite suivant la méthode NeON, offrant une approche claire et structurée (Suárez-Figueroa, Gómez-Pérez, Motta, & Gangemi, 2012a).

Le modèle sémantique proposé permet la diffusion et l'opérationnalisation du savoir du coût global pour les professionnels mais aussi pour les machines. En effet, la contribution principale de cet article est la proposition d'un cadre de connaissances accessible et réutilisable par n'importe quel agent logiciel souhaitant intégrer le calcul du coût global dans ses fonctionnalités. L'artefact contribue à ce projet de thèse en formalisant une approche du coût global à travers une ontologie, constituant une base solide et standard pour son instanciation.

1.8.3 Article 03 – A BIM-Ontology based platform for Whole Life Costing of building projects

L'article 03 finalise le projet de recherche en décrivant l'instanciation du modèle ontologique proposé dans l'article précédent. Basée sur la méthodologie de la RSC, l'étude propose le prototypage d'une plateforme sémantique. L'article en démontre le potentiel d'exploiter une ontologie pour l'approche du coût global dans les projets. L'instanciation programmée permet de gérer l'hétérogénéité et l'interopérabilité des données grâce à l'ontologie, reliant les concepts entre eux, mais aussi directement avec les sources de données. Ainsi, la solution contribue à la pratique proposant une approche d'ACG automatisée, basée sur les estimations préétablies.

La plateforme offre aux professionnels de faire varier chaque paramètre du coût global et de les modifier directement dans l'ontologie. De ce fait, le raisonnement automatique de ce modèle sémantique permet de tirer des résultats automatiquement, facilitant un travail d'analyse concentré sur l'interprétation plutôt que sur les tâches chronophages de récupération et traitement des données. Finalement, la plateforme a été conçue pour fonctionner avec des modèles BIM, permettant d'en extraire les données mais aussi de les enrichir de données du coût global. L'artefact proposé encourage un mode de travail ouvert, n'imposant pas de contrainte technologique aux acteurs des projets. Les données du coût global resteront accessibles dans les modèles à tout moment, facilitant son intégration dans les processus. L'article 03 contribue à ce projet de thèse en démontrant de façon claire comment l'ontologie du coût global peut être instanciée, et comment son instanciation

contribue aux projets. Les conclusions du projet permettent finalement d'identifier le potentiel de futurs travaux de recherche et opportunités basées sur cette technologie.

1.8.4 Articles de conférences – Annexes I et II

1.8.4.1 Article A – Exploring the synergies between Life Cycle cost / Whole Life Cost and Building Information Modeling: A Systematic Literature Review

L'article A présente une revue systématique de la littérature explorant la question des synergies entre le BIM et le coût global. L'investigation réalisée permet de contextualiser l'intégration de l'artefact proposé par la thèse dans l'environnement de construction numérique. L'article met en évidence les complémentarités entre le BIM et le coût global, et propose un cadre conceptuel qui structure les concepts, les processus et les méthodologies soutenus par leur intégration. Il contribue à la thèse en clarifiant les enjeux du BIM et le positionnement de l'artefact dans ce contexte, en l'alignant sur les défis d'intégration technologique et organisationnel d'autres types d'artefacts ayant les mêmes ambitions de proposer une approche BIM- coût global.

1.8.4.2 Article B – A case-study investigating the integration of ISO 19650 and OpenBIM principles

L'article B permet de comprendre les enjeux liés aux pratiques basées sur des données ouvertes et l'importance de leur considération pour l'artefact de cette thèse. Grâce à l'application de la norme ISO 19650 combinée aux principes de l'openBIM dans une étude de cas menée par la RSC, l'étude met en évidence des obstacles liés à l'interopérabilité. Ces résultats contribuent à la thèse en approfondissant la compréhension des problèmes technologiques et organisationnels qui contraignent l'échange d'informations dans les projets. Dans un second temps, l'étude a permis d'orienter la conception de l'artefact de la recherche en justifiant la nécessité d'encourager l'utilisation des normes ouvertes.

1.8.5 Rapport de recommandations

Élaboré dans le cadre de la Bourse Action Climatique 2023 du Fonds de Recherche du Québec – Société et Culture (FRQSC) portée par le Comité consultatif sur les changements climatiques, un rapport de recommandations a été rédigé afin de promouvoir l'intégration de la durabilité dans la construction grâce au coût global. Ce rapport explore le rôle du coût global dans le soutien aux stratégies durables dans l'industrie de la construction. Il contribue à la thèse en clarifiant le positionnement du coût global comme outil pouvant supporter le développement durable grâce à des prises de décisions éclairées. Le rapport présente notamment les complémentarités entre l'économie circulaire et le coût global, en montrant comment l'intégration de stratégies circulaires peut influencer les coûts du cycle de vie des projets et tout en démontrant les bénéfices environnementaux et sociaux. Le rapport fournit également des recommandations de politiques pour opérationnaliser le coût global en alignement avec les objectifs d'économie circulaire, encourageant l'idée que l'évaluation des coûts de projets doit évoluer pour intégrer la durabilité. Le rapport est disponible sur le site du Comité consultatif sur les changements climatiques :

<https://www.quebec.ca/productions-scientifiques-recipientaires-bourse-action-climatique>

Pour résumer la démarche entreprise, trois articles complémentaires ont été proposés. L'article 1 identifie les obstacles à travers un diagnostic organisationnel et propose une révision du rôle des experts en coûts de construction dans les projets, les positionnant comme utilisateurs finaux de la solution qui sera proposée. L'article 2 propose un cadre ontologique afin d'établir une fondation théorique du coût global. L'article 3 illustre une instanciation pour valider la contribution à la pratique, démontrant un exemple d'application de l'ontologie et proposant une approche accessible pour analyser et interpréter le coût global. Ces trois articles constituent ainsi une réponse intégrée au problème identifié, avec une analyse du contexte organisationnel et théorique, et une proposition d'une solution pratique adaptée.

CHAPITRE 2

ACCELERATING THE USE OF WHOLE LIFE COSTING IN CONSTRUCTION PROJECTS: A NEW ROLE FOR COST ENGINEERS

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2.1 Abstract

Purpose: The research aims to better understand the current and potential role that cost engineers can play in the implementation of a Whole Life Costing (WLC) approach in construction projects.

Design/methodology/approach: A grounded theoretical approach was employed, supported through a mixed method data collection strategy, utilizing data from two surveys and semi-structured interviews with cost engineers to explore WLC practices in the construction industry. Constant comparative analysis was used to develop a thorough understanding and better positioning of the role of the cost engineer in supporting the implementation of WLC-

Findings: Despite significant interest by industry practitioners in WLC, persistent barriers to its widespread adoption remain. Cost Engineers appear to possess the competencies and skills necessary to lead WLC implementation. This study proposes a reframing of the traditional responsibilities of Cost Engineers to support broader WLC adoption.

Originality: While WLC has been widely studied, little focus has been given to the responsibilities required to support its implementation. The study provides a thorough review of the actual state of WLC and the barriers to its adoption. The necessary conditions for WLC integration are identified. From there, the necessary responsibilities to make this approach a routine practice are defined.

Practical implications: This study defines practitioner responsibilities for the adoption and implementation of WLC. It suggests an evolution to the responsibilities of the cost engineer, involving it more in throughout the decision-making process. This redefined role represents an opportunity for Cost Engineers to develop their capabilities and strengthen their position within organizations and on projects seeking to implement a WLC approach.

Keywords: Whole Life Costing, Sustainability, Project Management, Cost Management.

2.2 Introduction

Sustainability has become a central concern within the construction sector. This imperative calls for more comprehensive design solutions which can improve an asset's resilience while reducing its impacts. While sustainable solutions can generate multiple benefits, they can also increase capital costs, hindering their implementation (Cole & Sterner, 2000). Early design choices profoundly influence a project's life cycle, with changes becoming increasingly challenging and costly as the project progresses (Bragança, Vieira, & Andrade, 2014). It is essential to anticipate the implications of a design decision across multiple factors to assess its potential benefits and inform effective design choices to deliver quality assets. To support this vision, assessment tools such as Life Cycle Assessment (LCA), which considers environmental impacts, or Whole Life Costing (WLC), which estimates the life cycle costs of projects, can support these design decisions (V. G. Larsen, Tollin, Sattrup, Birkved, & Holmboe, 2022).

In practice, LCA is increasingly used to analyse environmental impacts and has been made mandatory in some countries (Dodd, Donatello, & Cordella, 2021). But this is not yet the case with WLC, which remains underutilised in projects (Higham et al., 2015). The latter approach faces persistent challenge with integration into practice, its use remaining marginal today (Kambanou, 2020). WLC barriers are well established in the literature: Clients' lack of awareness and short-term vision, lack of reliable data, need for standard methodologies, and lack of political guidelines are presented as major obstacles (Muhammad Altaf et al., 2024 ; Higham et al., 2015 ; Olubodun et al., 2010). While the academic field has investigated and developed technical solutions to support WLC implementation, their application in practice remains very limited. D'Incognito (2015) indicates that the slow adoption of WLC and LCA stems less from technical limitations and more from organizational culture and entrenched practices. Indeed, the construction sector continues to operate within fragmented structures that hinders change and innovation. Consequently, it falls unto practitioners to take ownership of this shift by integrating life cycle thinking into their standard practice. Without their proactive involvement, WLC will remain confined to research rather than embedded in real-world project delivery.

From this perspective, cost engineers appear as one of the key actors in the operationalization of WLC within projects, bridging technical estimations and long-term decision-making. Cost engineers occupy a strategic position within construction projects, connecting technical design, economic evaluation, and managerial decision-making. Their role has progressively expanded from cost estimation toward integrated cost management, reflecting a transition from reactive calculation to proactive value interpretation (Ahiaga-Dagbui & Smith, 2014). This evolution mirrors the digital transformation of the industry, where cost data are no longer static but continuously updated to support design optimisation and life-cycle assessments (Smith, 2016). Cost engineers therefore operate as mediators between technical information and strategic choices, enabling the translation of complex project data into economic meaning. Their competencies in quantification, risk assessment, and forecasting support decisions concerning design quality and long-term investment performance (Alleman, Duval, & Molenaar, 2017). Their involvement in early project phases is critical, as

decisions made at that stage determine most of the life cycle costs and environmental impacts (Ahiaga-Dagbui & Smith, 2014).

In light of these considerations, the role of cost engineers is bound to evolve, transitioning from peripheral technical actors to professionals with the potential to guide strategic and sustainable decision-making. From this perspective, it is possible to ask: *What are the responsibilities of cost engineers in the operationalization of the WLC approach in construction projects?* Building on the attempts of Cole and Sterner (2000) of “reconciling theory and practices”, this study investigates the perceptions, interpretations, and applications of cost engineers in applying WLC in their professional activities. This research therefore aims to define the necessary responsibilities that cost engineers should possess to lead the application of WLC approaches to systematically support life cycle thinking in construction projects. To reach this goal, the study adopts a mixed-methods approach, with a grounded theoretical lens to analyse current estimation practices of cost professionals within the Canadian context and to understand perspectives on the application of WLC principles. The outcomes further refine understanding of the professional and organisational conditions shaping the integration of WLC within project organisations. A shift in focus of WLC research from method adoption to professional enactment is suggested. It highlights how cost engineers can play a leading role in the evolution of a vision that integrates key economic factors across the project life cycle. Hence, traditional cost estimation practices are reviewed to include WLC tasks, providing a framework to guide its operationalization. The paper begins with a literature review, exploring the notion of WLC and the gaps to fill. The methodology is then presented, followed by the results of the data collection. The outcomes of the analysis process and the resulting framework are presented and then discussed.

2.1 Literature Review

2.1.1 The evolution of Whole Life Costing

WLC is a financial estimation approach that considers all costs, direct and indirect, of an asset over its entire life cycle (Farr & Faber, 2018). Scholarly interest in life cycle costs can

be traced back to the end of the 19th century, such as in Sever and Fliess (1899) and Moses (1899), where data on operating expenses, resource consumption, and maintenance were collected and analysed to inform decision-making. However, the WLC methodology did not gain traction until the 1973 energy crisis, where the importance of design in reducing energy consumption was highlighted (B. H. Goh & Sun, 2016). This event catalysed interest in WLC, notably through the adoption of discounted present value techniques and the integration of probabilistic methods such as sensitivity analysis and risk management (B. H. Goh & Sun, 2016 ; Kishk et al., 2003). It is therefore a critical situation, through the energy crisis, that shone the spotlight on WLC. Today, standards like “ISO 15686-5:2017 Buildings and constructed assets Service life planning Part 5: Life-cycle costing” provide practical guidelines on calculations, costs to account and its integration into projects. Several frameworks structuring the application of WLC have been suggested over the past few decades, including stochastic modelling and fuzzy-based methods, which explicitly capture uncertainties in forecasting long-term costs (Goh and Sun 2016). Kirkham (2005) proposed an iterative WLC-based decision-making framework. The authors claimed the importance of having a continuous WLC, even during the post-construction phase to keep track of operational data, which represents the most challenging to forecast (Kirkham, 2005). Pearce (2010) defined a model based on WLC agents, describing the interactions of each agent in each of the design phases and demonstrating their impact on the final WLC of the project. Herrmann (2011) proposes the evaluation of the WLC to choose product maintenance strategies according to their conditions. These early frameworks established the methodological foundations of WLC, yet they remained largely technical and model-driven, with limited consideration for how professionals interpret and implement the approach within project organisations.

2.1.2 Extending the scope for sustainability

The growing complexity surrounding sustainability concerns highlights the need for professionals to be able to connect economic reasoning with environmental performance. Achieving sustainable development requires translating ecological strategies into economic

terms to guide resource allocation while accounting for externalities (Polasky et al., 2019). This perspective also calls for stronger interdisciplinarity between ecological and economic domains to bridge the gap between conceptual models and effective actions (Baveye et al., 2011). Hence, the need for sustainability has reignited interest in WLC. Environmental certifications such as BREEAM, HQE and LEED include WLC as an evaluation criterion. While there is currently no national policy framework in Canada that directly supports the use of WLC, some governments have attempted to promote its use, namely within the European context. The Level(s) framework, developed by the European Commission as a voluntary reporting tool for sustainable buildings, provides a structured approach to assess performance across six macro-objectives. Among them, Indicator 6.1 explicitly introduces WLC as a key component, encouraging practitioners to consider costs beyond the initial investments (Dodd, Donatello, & Cordella, 2021). The Level(s) framework also proposes a set of five design principles that reframe WLC as a strategic tool to support sustainable decision-making throughout the building lifecycle. These principles suggest that WLC should not be viewed solely as a reporting tool, but rather as an active component of the design process. The goal is not to deliver a financial figure per se, but to develop understanding of what drives long-term cost, and how choices at early stages influence future outcomes (Dodd et al., 2021). This framing contrasts with current practices in the Canadian context, where WLC is often treated as a late-stage or isolated evaluation step.

In the academic field, the approach has been employed to complement green concepts such as LCA (B. H. Goh & Sun, 2016). Schmidt and Crawford's (2018) framework uses WLC and LCA to optimise building design through multiple scenario options. Roh (2018) developed a streamlined environmental Life Cycle Costing model for buildings integrating environmental performance, focusing on the main costs, and building materials. These two studies demonstrate the efficiency and importance of this combination for environmental considerations. In the industrial sector, Janz (2006) proposed a Target Life Cycle Costing model, combining Target Costing and WLC, with environmental considerations. This approach happened to be an effective methodology, allowing the optimization of design considering specific functional and environmental requirements (Janz, Hornberger, &

Westkämper, 2006). In a previous study, other concepts and methodologies were identified as equally effective in supporting the decision-making process when combined with WLC: Circular economy, net zero emission, building life cycle management, waste management, life cycle sustainability assessment, triple bottom line, multi-objective optimization and value Engineering. This tendency reveals that defining cost implications through WLC is an effective decision optimization approach, hence it should not be considered in isolation (Gluch et al., 2018 ; Kirkham, 2005).

2.1.3 WLC in the context of digitalization of the construction sector

The digitalization of the construction sector has been an important subject of research over the past few decades. To this effect, the number of studies looking at BIM to exploit WLC has increased in recent years (Alasmari, Martinez-Vazquez, & Baniotopoulos, 2022 ; Muhammad Altaf et al., 2020). For instance, past studies have highlighted that BIM shows potential in facilitating WLC. Indeed, BIM can provide automatic quantity take-off and be used as a database, facilitating data management, simulation, and integration of the WLC earlier in projects. Khodabakhshian and Toosi (2021) described a framework using BIM and its fifth dimension, corresponding to cost estimation, to automate quantity take-offs of materials and amount of works. Santos (2020) defined an LCC/LCA process map that integrates BIM, describing the information exchange requirements of a model to foster WLC/LCA in the preliminary phases. In a subsequent study, the authors proposed a tool that allows the integration of WLC data directly into the model, facilitating automatic analysis, interoperability, and data management (Santos, Costa, Silvestre, Vandenbergh, & Pyl, 2020). Another study example from Apostolopoulos (2023) shows that the use of dynamic data-based renovation scenarios increases the quality of results. However, the literature on BIM has also emphasized that digitalization alone cannot ensure effective WLC analysis. As Smith (2014) underlines, the value of these technologies depends on the ability of cost management professionals to interpret, validate, and continuously update cost information within the 5D BIM environment. This shift requires estimators and cost engineers to develop

both digital and analytical competencies, allowing them to act as integrators of financial, technical, and temporal dimensions in decision-making.

2.1.4 Evolution of barriers to adoption of WLC

Despite the advantages of these new technologies, and its synergies with other concepts, WLC still requires work to become part of common practice. To elucidate this problem, this section revisits the barriers to the integration of WLC. Past research has identified several factors limiting the adoption of WLC, like the lack of motivation, thinking short-term, the complexity of the method, and not having easy access to reliable data (Cole & Sterner, 2000 ; Kishk et al., 2003). Cole and Sterner (2000) also conclude that WLC should not be used a simple comparison tool but as part of a larger decision-making framework. Kishk (2003) found that WLC has been caught in a vicious circle in which obstacles lead to less use of the WLC, thereby preventing opportunities to overcome them. Later, Olubodun (2010), conducted a survey in which 51% of the respondents (n=100) used WLC frequently, whereby 49% of WLC projects were initiated by client request. The author noted that the biggest barriers to WLC were the lack of understanding of the methodology, the absence of a standardised methodology, the complexity of the process, a perceived inaccuracy of results and an artificiality of the process. (Olubodun et al., 2010). Higham (2015) observed that only 41% of the respondents to their survey (n=49) were knowledgeable about WLC and highlighted through interviews that the most important barrier was the short-term budget horizon of the clients. Others barriers include the lack of awareness of the benefits, lack of client interest, and lack of expertise (Higham et al., 2015). Gluch et al.'s (2018) study concludes by revealing that while these previously identified barriers are frequently mentioned, WLC is more a matter of habit in terms of life cycle thinking in managerial routines. This means that professionals can adopt the approach, but they must overcome the lack of institutionalisation of the practice to attain WLC. Furthermore, the authors also highlighted that WLC calculations are mostly simplistic, with limited interpretation as well as the limited involvement of environmental and financial managers in decision-making processes (Gluch et al., 2018).

While interest in WLC adoption has grown, persistent barriers remain. In a recent study Bochare (2024), assessed the WLC awareness of over 500 participants including civil engineers, architects, and urban planners. The results show that 43% were familiar with the approach and 35% were well informed, but on the other hand 75% used traditional costing methods. Tsegai (2024) concluded from their survey (n=185) that the adoption rate of WLC is moderate and is influenced by user experience of the WLC tool used and its "fit-for-purpose" (Tsegai, Njuguna, & Aburili, 2024). The literature review reveals that a critical gap remains, as recent studies seem to repeat barriers that have long been defined.

As stated by Kishk (2003), broader application of WLC will reinforce its adoption through a positive feedback loop. This is supported in Gluch et al. (2018), highlighting that WLC is mostly an everyday task when a life cycle vision is adopted. Therefore, the fact that WLC is not "business-as-usual" is mainly due to lack of pervasive application. This begs the question: who's responsibility is WLC? Past research has indeed shown that there needs to be a responsible party to ensure its systematic use in project. In this sense, contrary to numerous studies that have investigated the involvement of a number of different actors without clearly laying out necessary responsibilities of particular roles and professional profiles, there is a need to focus on the parties that are directly involved in the cost management process, specifically, estimators and economists. Additionally, it seems that the literature, led by new technologies integration, is moving towards tool-centric research, forgetting previous lessons about the lack of integration of the approach into the project organisation. To bridge this gap, the research presented in this paper contributes to the field by continuing the discussion on WLC integration, focusing on professionals directly involved in cost estimation. If these actors are indeed the best candidates for this role, it is necessary to better understand how they interpret WLC in practice and what tasks can they perform to fully adopt WLC.

2.1.5 Role and responsibilities of Cost engineers in construction

Cost Engineering as a profession covers a wide range of technical, financial, and managerial activities supporting the economic control of construction projects. According to the Canadian Institute of Quantity Surveyors (CIQS), cost engineers are responsible for preparing and pricing quantity take-offs, bills of quantities, and tender documents; managing construction costs, contracts, and claims; performing feasibility studies, life cycle cost analysis, and risk assessments; and supporting negotiation and decision-making through cost control and forecasting activities (CIQS, 2015). Internationally, professional bodies such as the Royal Institution of Chartered Surveyors (RICS) emphasize similar competencies, highlighting analytical, advisory, and managerial dimensions of the role. The RICS identifies the cost engineer as a key actor, whose objective is to provide reliable cost information that supports informed decisions from project conception to completion (RICS, 2022). In the French context, the Cost Engineer is also recognized as a consultant ensuring the economic optimization throughout project development, acting as a link between design intent, technical feasibility, and budget constraints (Untec, 2025).

These definitions converge toward Cost Engineers acting as analysts, managers, and advisors simultaneously. However, as the construction sector transitions toward digital and sustainable paradigms, these traditional responsibilities must evolve. The integration of WLC is an opportunity to improve their missions to anticipate and interpret long-term economic implications across the asset's life cycle, providing more value into project delivery.

2.2 Methodology

2.2.1 Research Design

The objective of the research presented in this paper is to better understand the current and potential role that cost engineers can play in the implementation of a WLC approach in construction projects. This study adopts a mixed method design with a grounded theoretical approach. Grounded theory is a qualitative approach to research developed by Glaser and

Strauss (1967), in response to the criticism that the social sciences lacked robustness. The goal of this approach is to develop characterizations of phenomena based on the analysis of empirical data, rather than on logical deductions based on hypotheses (Glaser & Strauss, 1967). Since its inception, grounded theory has evolved and taken several paths, giving rise to classical (positivist), interpretive, and constructive grounded theory (Sebastian, 2019). In the context of the WLC application, this phenomenon can vary according to the user's point of view, giving rise to several interpretations. In addition, as mentioned earlier, the WLC has re-emerged as an important topic due to technological and climatic considerations. For these two reasons, this tends to justify the use of the interpretive grounded theory, which is based on the researcher's interpretation of the data and considers the theory as provisional and limited in time (Sebastian, 2019). However, to avoid a lack of representativeness of the complexity of construction projects, misinterpretation, and limit the biases of the researcher, this study adopted a pragmatic grounded theoretical lens (Charmaz, 2006 ; Rahmani & Leifels, 2018). The pragmatic grounded theory is proposed as a new movement of grounded theory by Rahmani (2018). The author suggests that this methodology is suitable for the construction sector as it will generate a contextualised "medium range" theory in direct response to practitioners' perspectives. Pragmatism makes it possible to link the principles of the different positivist, interpretative and constructive movements, adopting a point of view that brings together objectivity and subjectivity, and using qualitative and quantitative data (Morana, 2003b). Thus, Rahmani (2018) proposes a methodology that integrates abductive reasoning, and which also makes it possible to consider existing theories. The methodological process is shown in (Figure 2.1) and detailed in the following subsections.

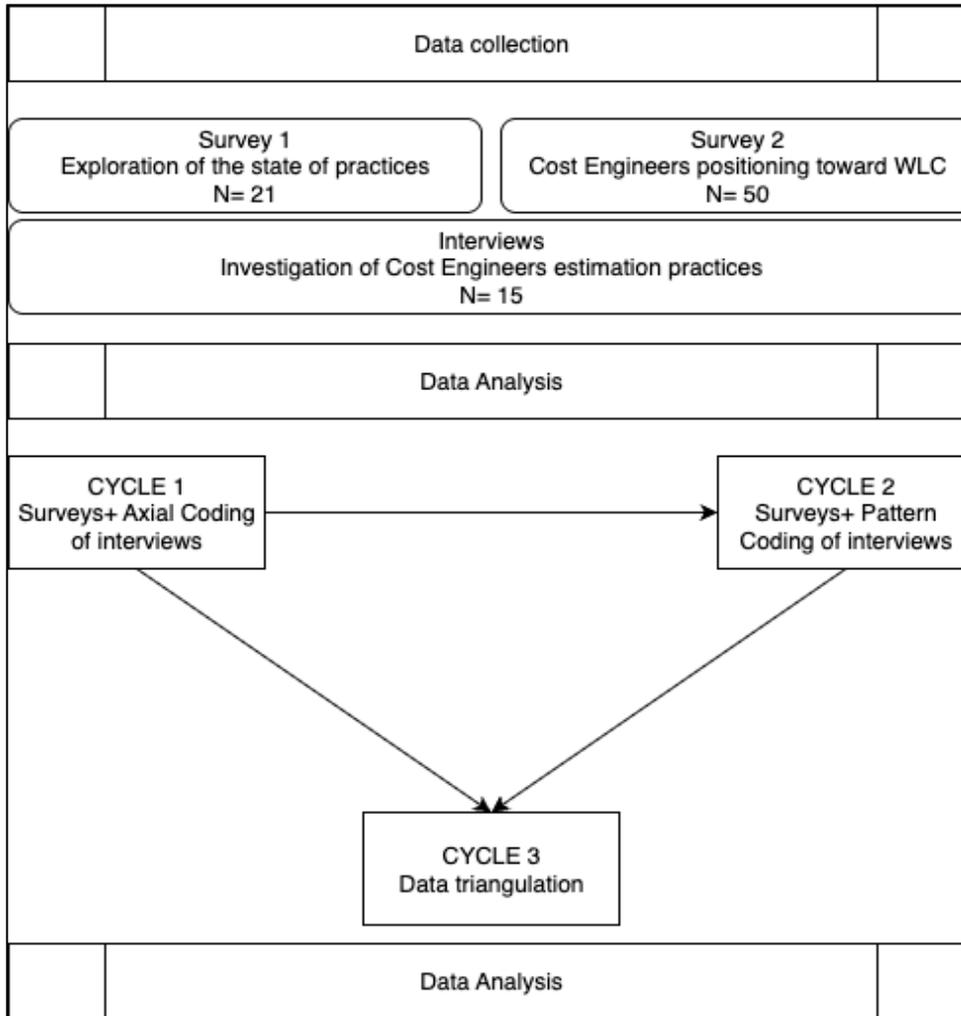


Figure 2.1 Project flow methodology based on grounded theory

2.2.2 Data Collection: Surveys & Semi-Structured Interviews

Data collection began with a survey investigating the current state of WLC knowledge and practice among construction cost engineers. The target population for this research was the Association des Estimateurs et Économistes du Québec (AEÉCQ), which distributed the survey to its members. 21 respondents participated in the survey, which was administered online.

The second step of data collection consisted in semi-structured interviews and were conducted with 15 professionals in estimating and construction economics. Based on the

previous results, the question that guided the discussions during the sessions were designed as follows:

- How do you define WLC? (Definition, issues, objectives, methodology, experiments, results, etc.)
- What do you see as the limits of the approach today?
- What improvements would be desirable to encourage its use?
- How can the WLC be used to internalise sustainable costs?

The aim of these interviews was to further investigate current practices and clarify the issues and needs of professionals in the industry. The sample of interviews is shown in Tableau 2.1.

Tableau 2.1 Sample of the semi-structured interview

Occupations	Participants	Private sector	Public sector	Research
Professor in environmental economics	2	-	-	2
Environmental Analyst	1	1	-	-
Asset management support	1	-	-	1
Estimator	6	5	1	-
Asset Manager	1		1	-
Economist	4	1	3	-

Among the interviewees, five people work in public institutions in valuation and asset management. Seven of them are part of private companies in environmental estimation and analysis. Three operate in research, including two as professors of applied economics and accounting working on the monetization of environmental impacts, and one as an asset management assistant project manager.

Of the participants interviewed, 4 completed a comprehensive WLC analysis, as presented in Tableau 2.2. For the remaining participants, three never applied WLC, two were involved in the analysis in a project, three indirectly applied the approach or concepts of cost planning

and forecasting, and 3 others never used these concepts but had knowledge and experience in asset maintenance.

Tableau 2.2 Profiles of participants who have carried out comprehensive WLC methodology

	Participant 1	Participant 2	Participant 3	Participant 4
Type of Project	Bridges and roads	Manufacturer product	Infrastructure	Buildings construction and equipment acquisition
Role	Public Owner	Consultant	Public owner	Public owner
Type of contract	Design-Bid	Service contract	Public-Private Partnership	Design-Bid
Type of LCC	LCC	WLC	WLC	LCC
Sustainability areas of focus	Economic	Economic & environmental	Social	Economic

Finally, a third survey was conducted to validate and extend previous findings with a broader group of professionals. With the understanding of the first results, the survey was designed to understand how to take action considering the context of practices of the professionals. This survey was a real-time survey, presented during a technical congress organized by the AEÉCQ. With 364 members in the association, the 50 respondents represent about 14% of the total population. While the goal of the survey was not statistical inference, this response rate still offers a meaningful cross-section of practitioner viewpoints for an exploratory study. In grounded theory, the purpose is not representativity, but the development of insights drawn from diverse experiences. In that sense, the sample was considered sufficiently rich to support the comparative analysis carried out in the subsequent cycles.

2.2.3 Data Analysis: Constant Comparative Analysis and triangulation

The data were analysed using the grounded theory approach applied to the semi-structured interviews, complemented by the survey data. The coding and interpretation process was guided throughout the principles of Constant Comparative Analysis (CCA), which ensured

continuous comparison across data sources and between emerging categories at each stage of the analysis. The CCA, which is the basis of the grounded theory methodology, allows for the development of a theory in line with empirical data (Glaser and Strauss, 1967). Each cycle of comparison was based on a different type of coding analysis of the interviews, allowing to highlight new insights to compare with the surveys. The CCA resulted in three cycles:

— Cycle 1: Understanding the conditions affecting the implementation of WLC
The objective of this phase was to identify the contextual and organisational factors that shape the current use or non-use of WLC. Axial coding was performed on the interview's transcripts,

— Cycle 2: Framing the operation requirements of WLC implementation
This phase focused on identifying the operational and contextual conditions that would enable broader WLC implementation. In this cycle, pattern coding was applied to interviewees' testimonials to reveal the drivers, their mechanisms, and the aims enabling WLC. All participant accounts were considered in the analysis, even if some of them never used WLC, as their perspectives related to concepts relevant to WLC, such as operational costs prediction, assets longevity or maintenance issues due to poor designs.

— Cycle 3: Defining the responsibilities of Cost Engineers to support WLC
Based on the previous cycles, a responsibility and competency table for Cost Engineers was developed. It represents how WLC could be practically integrated into the Cost Engineer's daily missions. The table used the CIQS description of duties for financial experts as a basis and show how it must evolve to integrate the WLC systematically in practice.

2.2.4 Validation of the study

Rahmani (2018) puts forward three aspects of research to which particular attention should be paid: Internal validity, which refers to the correspondence of the results with reality,

reliability, which refers to the consistency of the results with the data, and external validity, which refers to the applicability to other situations. In this study, internal validity and reliability were guaranteed by the CCA and the data triangulation, grounding the results in the data, and ensuring their consistency. Additionally, a research associate, independent of the project, peer-coded the transcripts for each cycle. To validate the reliability and consistency of the results, the associate's results were compared with the codes initially provided and discussed to reach a consensus. The notion of external validity, in a pragmatic grounded theory, is not limited to the generalizability of results, but also to their practical transferability. In this sense, the external validity of this study is operationalized through its capacity to generate a theory-in-action, one that can inform professional reflection and guide change in other comparable project contexts. The analytical generalization thus lies in the usefulness of the framework for transforming professional routines, rather than in the representativeness of the sample. Future studies could strengthen this validation by applying the proposed framework across multiple regions or professional settings, to evaluate its adaptability and impact on decision-making practices.

2.3 Results

2.3.1 Surveys results

Two surveys were conducted to assess both the current use of WLC and professionals' readiness to adopt it. The collected results are presented below in Tableau 2.3 and Tableau 2.4. The results of the first survey are characterized by the fact that 76% of respondents never applied WLC in their projects, and half of them had never heard of the approach. For those that had implemented WLC, a client initiated the approach for 60% of respondents, and WLC was initiated by the cost engineer in 20% of cases. In other cases, WLC was included as part of project delivery strategies, namely in the context of a Design-Build-Finance-Maintain mandate and another as part of an economic evaluation.

Respondents were also asked about the reasons why they had not used WLC in the past. The most selected answers were "lack of time" and "lack of knowledge." These responses are

closely followed by the “lack of demand” and “lack of tools”, while among the “other” responses, the three respondents specified, “never had to use it,” “contractual barriers,” and “not applicable”. The second survey complement these results, highlight “fragmentation of data” as a main cause, which 86% of respondent identifying it as a significant barrier to WLC. Furthermore, 34% of respondent ranked either the “need for reliable data” or a “common understanding” of WLC as their first concern. “Structured process definition” was ranked first by 14% of respondents, followed by “Integration of fragmented data” and “existing tools”, both of which were ranked first by 10% of the attendees.

Tableau 2.3 Survey 1 Results

Question	Results
Q1. Have you ever witnessed or practiced the approach in a project? N= 21	38 % Never heard of it / 48 % Witness / 9 % Analysis leader / 5 % Analysis interpreter
Q2. In what context was the approach conducted? N= 13	60% Client request / 7% Certification / 20% Estimator proposal/ 13% Other (Design–Build–Finance–Maintain mandate - Economic evaluation)
Q3. Why didn’t you use the approach? N= 19	26% Lack of time / 26% Lack of knowledge / 5% Lack of Skills / 21% Not requested / 16% Lack of tools / 16% Other (“never had to use it” - “contractual barriers” - “not applicable”)
Q4. Do you think the approach has the potential to improve construction investments? N=21	81% Yes / 19% No
Q5. Do you think the approach has the potential to improve the role of estimators in projects? N=21	76% Yes / 24% No
Q6. What would you need to start using this approach? N=20	33% Training / 31% Client requirement / 13% Software / 13% databases / 10% Others (Contractual modification - early collaboration)

Tableau 2.4 Survey 2 Results

Question	Response	Percentage
Q1. Do you think adopting WLC is logical step in adopting new technologies? N = 50	Yes	94%
	No	6%
Q2. Would you be ready to use this approach in the near future (within 5 years)? N = 50	Yes	88%
	No	12%
Q3. 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%
Q4. Do you feel that the information needed is currently too fragmented between systems and stakeholders? N = 50	Yes	86%
	No	14%

The second survey investigated the perception that cost engineers had of adopting WLC in the future. Among the 50 professionals questioned, 94% were aware of the importance of WLC considering technological improvements in the construction sector, and 88% seemed ready to engage in its adoption in the coming years. Additionally, the first survey reveals that most estimators (76%) believe that the approach could serve to bolster the role of estimators in projects. Moreover, 81% of respondents thought that using this approach would improve investments. Thus, practitioners still demonstrate an interest for WLC approach, but they also express the need to be supported in this activity. The main needs felt by estimators and economists are the need for training (33%) and customer demand (31%). There is also a need

for appropriate 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”.

2.3.2 Cycle 1: Understanding the conditions affecting the implementation of WLC

To better understand the complexity involved in WLC integration, axial coding was carried out on interviews of WLC-experimented practitioners’ transcriptions, targeting practical problems experienced by them. Related problems have been grouped into categories below (Tableau 2.5). Among the most cited obstacles, “lack of data” (23 instances), “lack of methodology” (18 instances) and “lack of skills” (13 instances) correspond directly to the survey’s concerns about knowledge and tool availability. The “lack of collaboration” (15 instances) and “short-term vision” (9 instances) reflect a lack of shared vision within project teams, which perhaps explains why the WLC is rarely initiated by the analysts themselves. This idea is supported by the fact that customers are the main initiators of WLC use. Such dependency on client demand indicates that responsibility for long-term evaluations is not yet structurally shared across project stakeholders. This is in line with interview comments, which indicate that reluctance to take responsibility for long-term predictions (9 instances) and uncertainties (8 instances) are major obstacles. In addition, lack of resources, political influence and information fragmentation echo the other reasons mentioned in the survey, such as contractual limitations, initiation through certification and the choice of using another economic analysis.

Tableau 2.5 Practical problems of WLC application

Practical problems	Number of instances in transcripts
Lack of Data	23
No available methodology	18
Lack of competencies	13
Hesitation to take responsibility for predictions	9
Lack of collaboration	15
Short-term vision	9
Lack of resources	8
Uncertainties	8
Lack of tools	9
Political influence	6

Surveys and interviews reveal that the main barriers to implementing WLC analysis are lack of time, knowledge, and demand, as well as data fragmentation and the need for reliable data. Interviews with experienced practitioners highlight additional challenges such as lack of collaboration, short-term vision, and reluctance to take responsibility for long-term evaluations. These findings can be interpreted as a major cultural barrier, as the client is actually the main requester of the analysis. Indeed, the latter may not be aware in the possibility to implement WLC, asking for other economic evaluations, thus not giving the time for Cost Engineers to consider the WLC in their analysis. Moreover, the lack of shared vision and collaboration may create a reluctance within projects teams to allow the Cost Engineer to perform a WLC analysis. This situation reveals a structural limitation, due to the fact that clients rarely have the technical capacity, access to appropriate data, or the methodological framework to initiate or sustain WLC analyses. Expecting them to lead the process therefore perpetuates its underuse. A shift is therefore needed, towards a professional leadership model in which a qualified actor takes ownership of the approach, ensures consistency across stakeholders, and embeds WLC as a systematic component of project

delivery. The next cycle explores the capacity of Cost Engineers to assume this role and guide the practical integration of WLC within construction practices.

2.3.3 Cycle 2: Framing the operation requirements of WLC implementation

This phase aims to explore the conditions that facilitate the WLC implementation by Cost Engineers. Pattern coding has been employed to analyze the diverse practices of Cost Engineers. Results of the coding are presented in (Tableau 2.6) below.

The difference of experimented-WLC participants behaviour was about looking for opportunity costs to get future savings, reduce project impacts and project transparency. Among practitioners, WLC tends to be primarily used to identify potential future monetary benefits, contrary to non-WLC users who are tracking immediate benefits through return on investment (ROI), investment savings and Target Cost as outcomes of the value analysis. WLC users interviewed used Net Present Value (NPV), Target Cost, ROI, and investment and operational savings to optimise costs. The main difference lies in how users evaluate the methodological effort and interpretive depth of the approach.

This was highlighted by one of participant who was looking to implement circular economy strategies. This detail confirms the real value of WLC is not to find the NPV of a certain item at a certain point in time, but to assess the processes involved in getting to that point. In fact, the same principle was used by non-users of WLC to evaluate environmental works to comply with regulation during the construction phase. The designers implicitly considered effort, which they translated into costs, to estimate the work to be done and avoid costs associated to regulatory compliance. Thus, WLC should be considered for its interpretative value, aiming to capture and understand the processes appearing in the life cycle of infrastructures.

Tableau 2.6 Pattern Coding analysis

	Participants with WLC experience	Participants without WLC experience
What objectives are aimed?	Opportunity costs for future savings Optimise investments Reduce project impacts Project transparency	Optimise investment costs
How they proceed to reach them? (indicators used)	Net Present Value, Target Cost, Return on Investment (ROI), savings, Estimating the efforts	ROI, savings, Target Cost
Why they wanted to reach them? What was to be achieve?	Procurement Asset management Circular economy PPP Environmental regulation works Environmental taxes Planification Innovation	Procurement Asset management Value analysis Planification Environmental regulation works

Surveys and interviews reveal that, regardless of their experience with WLC, cost engineers share the common objective of optimizing investment. It also reveals that they both have the capacity to consider designs choices financial impacts in their reasoning. Even when the WLC methodology is not explicitly applied, professionals already handle indicators such as ROI, Target Cost, and savings over time, demonstrating an implicit understanding of life cycle thinking. However, the primary distinction lies in their patterns of thought. Traditional estimation focuses on reducing initial costs to benefit the client's wallet, but not the project's objectives. Among experienced WLC practitioners, this perspective extends further to include opportunity costs, suggesting a more interpretative and strategic use of cost data.

The first survey indicates that cost engineers acknowledge the potential of WLC to enhance their practices. The second survey shows that most of them are ready to adopt this approach. Considering these findings, it can be said that WLC does not appear overwhelming to them

and is even perceived as an advantageous opportunity for their future practices. Moreover, as experienced by experts, adopting a life cycle perspective is already within their field of competency. Thus, they already possess the capability to implement this approach effectively. The results therefore suggest that cost engineers are suitable candidates for WLC leadership. While clients and design teams often lack either the technical expertise or the mandate to lead WLC, cost engineers already possess the analytical tools and the economic vision required to assume this role. Their role positions them as natural mediators capable of aligning short-term constraints with long-term project outcomes. Recognizing and formalizing this role appears to be the next step toward embedding WLC as a standard, proactive component of project delivery. The following cycle builds on this insight to outline a renewed role for cost engineers, integrating life-cycle responsibility and interpretative leadership into their professional framework.

2.3.4 Cycle 3: Defining the responsibilities of Cost Engineers to support WLC

Leading the implementation of WLC in a systematic manner means that it should become an everyday way of thinking for Cost Engineers (Gluch et al., 2018). Thus, WLC should shape its daily estimation tasks. Along with the insights provided in the previous cycles and based on the CIQS list of duties of the cost engineers, the Tableau 2.7 present how these tasks can evolve to reach this perspective.

Tableau 2.7 A new role for Cost Engineers

Original CE duties stated by the CIQS	Revised Tasks integrating WLC Vision
Preparing and pricing quantity take-offs including analytic estimating.	Preparing and pricing quantities take-offs while integrating operational, maintenance, and end-of-life costs from early design stages.
Preparing bills of quantities.	Preparing bills of quantities aligned with life-cycle cost structures.
Preparing, pricing, and submitting tenders/proposals	Preparing, pricing, and submitting tenders/proposals along with WLC analyses in proposals to support long-term investment and sustainability decisions.
Reviewing tender/proposal documents	Reviewing tender/proposal documents based on life-cycle value and performance rather than upfront price alone.
Managing, administering, and coordinating construction projects/contracts	Integrating WLC as a contractual and performance management tool throughout project delivery.
Preparing, forecasting, and reporting construction costs	Preparing, forecasting, and reporting life cycle costs.
Preparing economic feasibility studies	Preparing economic feasibility studies that consider environmental and social externalities across the asset's life cycle.
Preparing life cycle cost analysis	Lead, interpret, and communicate WLC analyses as collaborative and iterative decision-making tools.
Identifying, evaluating, analyzing, and managing risk	Identifying, evaluating, analyzing, and managing risk across the life cycle, covering future costs, uncertainty, durability, and performance.
Providing advice on construction cost control and planning	Act as a strategic advisor integrating long-term cost and sustainability considerations into project planning.
Preparing and maintaining unit price databases	Preparing and maintaining unit price databases and keeping track of life cycle costs
Preparing and monitoring construction progress schedules	Align project schedules with life-cycle cost data to anticipate economic and maintenance impacts.
Establishing and implementing cost control process	Establishing and implementing cost control process integrating performance, durability, and life-cycle efficiency indicators.
Collaborating in value management strategies	Collaborating in value management strategies considering long term added value
Supporting negotiation with stakeholders	Supporting negotiation with stakeholders by offering transparency and collaboration through life cycle costs
Preparing and reviewing replacement and loss cost analysis	Preparing and reviewing replacement and loss cost analysis to inform design and maintenance strategies from project inception.

A life cycle vision should shape Cost Engineers' behaviours from the very onset of the project. Hence, core tasks including preparing and pricing quantity take-offs should evolve to incorporate not only construction costs but also maintenance and end-of-life costs from the earliest design stages. This shift transforms traditional estimation into a proactive process

implying that life cycle data should be available from the beginning of the project. Consequently, Cost Engineers may need more extensive databases and more robust data architectures, supporting stronger basis of hypothesis for analysis. To do so, the preparation of bills of quantities should namely align with standardized life cycle cost structures, ensuring consistency and comparability of results across project phases. As guided by ISO 15686-5, these cost structures can evolve among the different stages of the life cycle. Likewise, the development and maintenance of unit price reference databases must include life cycle information to enable continuous updating and benchmarking of long-term costs. Replacement and loss cost analyses should also be integrated into early design stages to inform maintenance and renewal strategies before construction even begins. By aligning quantity take-offs, bills of quantities, price databases, and replacement analyses under life cycle cost frameworks, Cost Engineers can establish a common thread of costs between the different stages of the project life cycle that supports transparent interpretation, comparison of alternatives, and proactive maintenance planning.

Integrating WLC into construction practice requires a shift in how collaboration and decision-making are structured across project stakeholders. Cost Engineers must move beyond traditional cost evaluation to act as facilitators of long-term value creation. A valuable citation of one of the interviewees say: *“The problem isn’t really the tool that’s going to make it work, but the problem is tying all the people in the industry around the same process to make it work”*. This insight directly reflects the barriers of short-term vision and the fragmented nature of construction project stakeholders, where each actor primarily seeks to optimize their own margin rather than the project performance. Cost engineers are in a unique position to counter this fragmentation, by leading discussions around life cycle trade-offs, they can connect technical feasibility, economic viability, and sustainability objectives. By embedding WLC principles into value management discussions, Cost Engineers can help redefine “value” in collective rather than individual terms, making long-term performance a shared goal rather than a constraint. However, improving negotiation with, and between, stakeholders require time and transparency. This can be supported by WLC with costs data as a common language.

This collaborative mediation role strengthens trust and aligns stakeholder decisions toward shared long-term benefits. However, as one participant pointed out, WLC is often applied only in a “partial” way for comparing isolated elements, which limits its capacity to support transparent negotiation and shared decision-making. Thus, preparing, pricing, and submitting tenders or proposals should systematically include WLC analyses to provide investors and owners with long-term financial projections, not just upfront prices. Integrating WLC at this stage also responds to the barrier of client dependency, repeatedly identified in surveys and interviews, where cost engineers apply WLC only upon explicit client request. If life cycle evaluation becomes a standard deliverable in tender preparation, the initiative shifts from reactive to proactive practice, positioning the cost engineer as a driver of WLC. Similarly, reviewing tender or proposal documents should evolve from comparing unit prices to assessing life-cycle performance and value. Finally, the task of managing, administering, and coordinating projects and contracts must evolve toward integrating WLC as both a contractual and performance management tool throughout project delivery. It can address the lack of shared responsibility observed by participants, which appears to be concerned about potential consequences. One participant stated: « *When we make an estimate of the work, we have a commitment for these prices. If the client starts to request us for environmental and/or future costs, it becomes complicated for us.* » It is crucial to ensure that decisions affecting long-term cost and performance remain traceable and collectively owned.

The cost management activities of cost engineers should evolve to systematically integrate life cycle costs into the preparation, forecasting, and reporting of construction expenditures. Life cycle thinking must inform these activities from the earliest project stages, including the economic feasibility studies. At this phase, cost engineers can evaluate macro-objectives and internalize environmental and social externalities across the asset’s life cycle, enabling a more comprehensive definition of value. WLC analyses thus becomes not a one-time computation but a continuous interpretative process, dynamically updated as design and operational knowledge evolve. Cost engineers should therefore lead, interpret, and communicate WLC analyses as a collaborative and iterative decision-support tool. This

element is essential for the credibility of the project, because as said by a participant: *“If you don’t have data, it means you have no idea how your structure will hold up over time, whether it will need to be maintained in 15, 20 or 25 years. You’re just saying that theoretically it’s good for 25 years, and in fact, you have no idea.”*

In this sense, identifying, evaluating, analysing, and managing risk should cover future costs, uncertainty, durability, and performance throughout the life cycle. Furthermore, this evolution addresses practitioners’ reluctance to assume responsibility for long-term forecasts, as one interviewee noted, « It is challenging to predict costs over several decades in a deterministic manner, » particularly when « there is no knowledge of how your structure will withstand time due to missing data. » Instead of an uncontrolled variable, it can reframe uncertainty as a quantifiable, traceable dimension of cost planning. Furthermore, it is becoming essential to assist clients with the long-term financial implications of their projects. Cost engineers must align project schedules with life cycle cost data to anticipate economic impacts and maintenance costs, ensuring that strategic choices remain consistent with initial investment objectives. Thus, the task of establishing and implementing cost control processes that incorporate performance and sustainability indicators makes it possible to evaluate decisions from both an immediate and a future perspective. This expanded interpretative role requires not only methodological proficiency but also new competencies in strategic communication, data interpretation, and systems thinking, which should be further defined and integrated into professional development and training.

2.4 Discussion

The objective of the research presented in this paper is to better understand the current and potential role that cost engineers can play in the implementation of a WLC approach in construction projects. The three research cycles show that the main obstacles to WLC are structural rather than technical, and that professionals already handle methods and indicators aligned with life cycle reasoning. The table resulting from the evolution of tasks therefore

redefines current practice towards a role for the Cost Engineer that is rooted in a life cycle perspective.

This repositioning aligns with a broader professional transformation toward structured cost engineering systems (Didkovskaya et al., 2016) and advanced digital practices such as 5D BIM (Smith, 2016b). Emerging technologies, including quantity automation and 4D/5D integration, are redefining the cost manager's role as a data integrator capable of producing living cost plans that are continuously updated in near real time, comparing multiple design scenarios, and supplying ongoing economic insights throughout design and construction (Smith, 2016a). This data-driven and advisory role closely matches several tasks proposed in the WLC table, particularly the integration of operational, maintenance, and end-of-life costs from the earliest project phases, and the use of WLC data as a tool for negotiation and contractual steering. By internalizing WLC principles into cost management routines, cost engineers can enhance methodological rigor while embodying a decision-support function within project organizations.

Didkovskaya et al. (2016) emphasized the need to connect investment, estimated, contractual, actual, and operational costs within a coherent national and corporate cost engineering system. Similarly, Beznebeeva and Vodopyanova (2019) argued that professional training should produce versatile specialists capable of managing costs at all stages of the project life cycle. These findings directly resonate with the WLC framework presented in this paper, which proposes to reinterpret traditional cost engineering responsibilities in light of the evolving construction context and its digital and sustainability requirements.

However, achieving the level of rigor required for WLC practice remains challenging, as reflected in both survey and interview findings. The most frequently reported obstacles directly compromise the reliability of long-term cost estimates. Standardization thus emerges as both a methodological and organizational imperative, forming the technical foundation for harmonizing cost data across design, construction, and operation, and for restoring continuity

in data use throughout an asset's life. Interviews also pointed to persistent issues of data fragmentation and unclear responsibility. Integrating cost databases within digital modelling environments such as BIM directly responds to professionals' demand for integrated processes and interoperable tools that enable validation and traceability of economic data.

In this regard, Smith (2016b) identified several persistent issues associated with the implementation of BIM and 5D. These include the absence of comprehensive models, the reluctance of designers to share complete models, inconsistencies in modelling and classification standards, and the absence of stable national or international frameworks for model-based quantity measurement. These challenges pose a significant obstacle to cost engineers in conducting reliable WLC analyses based on digital models, despite the theoretical availability of relevant tools. More broadly, the literature and this study converge on the same systemic fragmentation. Many clients remain unaware of the benefits of WLC, contractual frameworks continue to prioritize initial costs, and professional cultures still favor short-term control instead of long-term value creation. The proposed WLC framework does not remove these barriers but makes them explicit by showing how reorienting professional duties toward long-term value could help overcome them.

The cost engineer, therefore, is no longer merely an operator of estimation methods but an active stakeholder in value creation within construction projects. Beyond its disciplinary contribution, this study reinforces the notion that the theory and practice of WLC are inseparable. While earlier research has emphasized methodological or technological refinements, the effectiveness of WLC ultimately depends on the social configuration of professional roles and the collective capacity to interpret cost information over time. The revised CIQS task framework exemplifies this expanded role. The cost engineer evolves from a specialist in quantities and pricing to an interpretive and collaborative actor in project development. As Smith (2016b) noted, cost managers must develop critical analysis, communication, and data management skills to support collaborative design processes. The WLC vision advances this notion further, explicitly positioning the cost engineer as the expert of economic coherence throughout the entire life cycle. For instance, transforming the

task “prepare economic feasibility studies” into “include environmental and social externalities” elevates the professional’s responsibility to translate sustainability principles into economic language. Similarly, redefining “prepare replacement and loss cost analyses” as “inform design and maintenance strategies from the earliest stages” situates cost engineers as essential interlocutors for facility managers and asset operators. This evolution aligns with Beznebeeva and Vodopyanova’s (2019) call for cost engineers capable of managing complex cost systems, engaging with regulatory bodies, and ensuring transparency and robustness in cost forecasting. Explicitly embedding WLC principles within project governance could also redistribute accountability for long-term performance. Such transformation would shift responsibility from an individual burden borne by cost engineers to a collective process shared among all project participants, addressing the structural fragmentation that currently limits WLC adoption.

Future studies should explore how to provide Cost Engineers with access to an effective and intuitive WLC tools and methodology to support them. Apart from this technical aspect of analysis, the decision making and the data management should also be reviewed. The data management aspect means getting the right data at the right time to ensure precise analysis. This is the responsibility of all stakeholders to collaborate adequately to ensure a comprehensive and useful WLC application. Hence, the project data management process should be defined to improve this aspect. The work should identify data location, their owners and the exchanges requirements. Furthermore, new Information Technologies and Knowledge Management Techniques should also be studied to facilitate this data management. In parallel, pilot projects should be conducted to test the practical implementation of the proposed framework. Such empirical testing would validate whether the new duties and responsibilities effectively support WLC integration, improve collaboration, and influence decision-making quality within real project environments.

The use of the grounded theory methodology provides a solid theoretical foundation for understanding the challenges and needs for the adoption of WLC. However, to further explore this avenue, a more detailed study, particularly with a larger sample for data

collection, could improve the results. Instead of generalizing the findings statistically, the study focuses on their usefulness for understanding and improving practice. In a pragmatic perspective, validity comes from the ability of the framework to inform action across comparable professional contexts. Future research could therefore extend this study by replicating the approach across multiple professional and geographical settings to evaluate how the proposed framework operates in different project environments. Comparative studies could refine and expand the theory-in-action derived here, strengthening both its explanatory power and its capacity to guide practice. Such extensions would not test universality but would assess whether the mechanisms identified hold relevance across diverse construction ecosystems.

2.5 Conclusion

The present study explored the WLC approach application in Cost Engineers practices to answer the following question: *What are the responsibilities of cost engineers in the operationalization of the WLC approach in construction projects?* To do so, the study started with a literature review looking at the WLC historical evolution. Among the common barriers mentioned, a critical problem has been identified: WLC suffers from a lack of application. This problem, that can be related to the absence of shared responsibilities, leads to insufficient use of the approach and thus insufficient solutions development to overcome its barriers. Indeed, most professionals indicated, in line with the literature, that WLC is mostly initiated by the client. This situation is explicable as professionals have a responsibility upon their estimations results and thus fear the contractual consequences as WLC is uncertain in nature. However, if the client is unaware of this approach and other project team members are hesitant to take a risk, how can WLC evolve? A solution to this problem is for cost engineers to assume the lead and be empowered to promote its use. Furthermore, WLC should be part of everyday practices, as it is more about adopting a vision than conducting an isolated exercise. This implies that cost engineers must take the responsibility to enhance their common practices and resources to evolve towards a more proactive and involved role.

The paper also proposed an exploration of current building cost engineers' practices and their perceptions on WLC through two surveys and semi structured interviews. Thanks to the pragmatic grounded theory and its method of constant comparison analysis, collected data confirmed the needs and expectations of practitioners toward the application of WLC application in construction projects. Based on this the cost engineer's role is reconsidered through a comparative framework. The implications of this framework are discussed, highlighting the need for cost engineers to take responsibilities and develop the necessary competencies to initiate the approach within projects. By assuming this proactive role, they can also help redistribute accountability across the project team, transforming the individual burden of responsibility into a collective process shared by all stakeholders. This represents an opportunity for them to make their profession evolve and gain more value. Indeed, new technologies will eventually facilitate WLC application, thus providing more leeway for the interpretation and decision-making support. Nonetheless, it is also important that the whole project team support the cost engineers as WLC should be a collaborative methodology that optimise project design. The paper contributes to the existing body of knowledge by reviewing the evolution of WLC and framing a discussion on its future integration into the actual construction context, namely by reframing the cost engineer's role and responsibilities to lead and proactively support WLC implementation.

While this study offers new insights into how WLC can be better understood and applied by building cost engineers, certain limitations remain. Conducted within the Canadian context, the findings reflect a specific professional and policy environment. The proposed framework has not yet been validated through design processes or tested on real projects, which limits its applicability. Moreover, the reconceptualization of the role of cost engineers, although grounded in practice, remains at a conceptual level and would benefit from further theoretical refinement and alignment with existing practices. Future research could investigate how this role can be further operationalized in practice, by identifying the precise tasks and activities to be undertaken and their supporting tools and technologies. This could contribute to clarifying the domain of WLC itself and support a more integrated understanding of its role

within decision-making in the construction industry. In line with the pragmatic orientation of this research, future studies should empirically test the proposed framework through pilot projects and case studies, to evaluate how these new duties operate within real organizations and project environments. Such validation would ensure the framework's usefulness and transferability to comparable professional contexts. Future research could also examine the techniques currently used for WLC, to determine whether they still meet the information needs, constraints and decision-making processes of stakeholders. This refinement would not only clarify the scope of WLC within the discipline but also support the development of trainings that align cost engineers' evolving responsibilities with life cycle value creation. This would help determine whether current tools and methods, and those under development, are fit for purpose, or whether they need to be reoriented to better support project needs.

2.6 Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CHAPITRE 3

A CORE ONTOLOGY FOR WHOLE LIFE COSTING IN CONSTRUCTION PROJECTS

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3.1 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)

3.2 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 (Adepu, Kermanshachi, Pamidimukkala, & Loganathan, 2024). Broad sources of uncertainty, from data scarcity (Biswas & Zaman, 2019) to construction execution quality (Francis, 2017), and long-term uncertainties, concerning energy usage and environmental impact throughout the building life cycle (Zong et al., 2024), 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 (Zong et al., 2024). Moreover, uncertainty simulation tools facilitate the modelling of alternative scenarios, thereby aiding project planning (Francis, 2017).

Additionally, risk assessment methods contribute to the quantification of uncertainties and facilitate the identification of potential consequences associated with decisions (Biswas & Zaman, 2019). 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 (Daoud, El Hefnawy, & Wefki, 2023). 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 (Aziz & Abdel-Hakam, 2016). 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 (Naoum, 2010). 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) (Oesterreich & Teuteberg, 2016). BIM, at the center of this digitalization, is defined by ISO 19650-1 2018 (« ISO 19650-1:2018(en)) 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 (Kambanou, 2020).

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 (Farr & Faber, 2018). WLC is a “methodology for systematic economic consideration of all cost and benefits over a period of analysis, as defined in the agreed scope” (ISO, 2017). Since its first applications, this approach has been used to determine the best alternatives for projects (Cole & Sterner, 2000). 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 demonstrate the real implications of investment costs (Hunkeler & Rebitzer, 2003). 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 (Swaffield & McDonald, 2008). A previous study concluded that BIM can bring many technological advantages enhancing

WLC (A. Yousfi, Poirier, & Forgues, 2022). Alsamari (Alasmari et al., 2022), 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 (Muhammad Altaf et al., 2020), 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 (Lu, Jiang, Yu, Tam, & Skitmore, 2021), 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 (Pauwels, 2014). Hence, in (Boje, Guerriero, Kubicki, & Rezgui, 2020), 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 (Pauwels, McGlenn, Törmä, & Beetz, 2018). 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 (Berners-Lee & Hendler, 2001). The goal is to represent the fundamental structure of concepts and to provide all of the vocabulary necessary to build a shared knowledge base (Mizoguchi, 2004 ;

Ostrowski et al., 2014). 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 (Roussey, Pinet, Kang, & Corcho, 2011). 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 (ISO, 2017), 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.

3.3 Literature Review

3.3.1 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 (Farr & Faber, 2018). The approach can be used to evaluate projects, forecast the performance of new technologies, allocate resources on important items, or conduct negotiations (Cole & Sterner, 2000 ; Kishk et al., 2003). 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 (Kishk et al., 2003). 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 (Olubodun et al., 2010). 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 (Higham et al., 2015 ; Roda et al., 2020). 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 (Boussabaine & Kirkham, 2004 ; Cole & Sterner, 2000 ; Higham et al., 2015). 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 (Pearce et al., 2010). 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 (Cole & Sterner, 2000). 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 (Roda et al., 2020). This activity can therefore be very time-consuming for the estimator (Kishk et al., 2003).

Historical data must be reported on a basis comparable to the context of the new project, which can sometimes be difficult (Teshnizi, Pilon, Storey, Lopez, & Froese, 2018). 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 (Boussabaine & Kirkham, 2004 ; Cole & Sterner, 2000 ; Olubodun et al., 2010). This subjectivity implies a risk of over- or underestimating the WLC of the project (Jafari et al., 2014), though the involvement of the human factor increases the risks resulting from estimation (Xinghua Gao et al., 2019). Thus, the inherent challenge of WLC is to make the right assumptions, as early in the project as possible, when little information is known (Pearce et al., 2010). Missing or inaccessible data can also reduce confidence in the calculation, which requires predictions. Indeed, in (Pearce et al., 2010), 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 (Boussabaine & Kirkham, 2004).

3.3.2 Ontologies for Construction Projects

W3C establishes standards and guidelines to enable the creation of a web that prioritizes accessibility, internationalization, privacy, and security (Pauwels, 2014). The concept of linked data presents a set of good practices to reach this vision, as follows (Pauwels, 2014):

- 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 (Partridge et al., 2020). 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 (Godager, 2018). 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 (Niknam & Karshenas, 2017a ; J. Pan, Anumba, & Ren, 2004). In a construction project, the same element can take on distinct characteristics depending on the context in which it is used (J. Pan et al., 2004). The process to make contextualized data available is semantic data integration, which adopts a conceptual representation of data and their relationships (Cruz & Xiao, s.d.). In (J. Pan et al., 2004), 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 (Mercier, Cheong, & Tapaswi, 2018), has concluded that ontology is a comprehensive tool to unify heterogeneous data from various sources. Ontologies serve 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 (Niknam & Karshenas, 2017a). 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 (J. Pan et al., 2004).

Several ontologies for describing the construction context have been proposed (Pauwels et al., 2018). 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 (Rasmussen, Lefrançois, Schneider, & Pauwels, 2021). 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 (Zheng, Törmä, & Seppänen, 2021). An IFC ontology, ifcOWL has also been proposed to ensure proper use of BIM models with ontologies (Pauwels, Krijnen, Terkaj, & Beetz, 2017). 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.

3.3.3 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 (Ma, Wei, & Liu, 2013). 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 (H. Liu et al., 2016), 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 (Abanda, Kamsu-Foguem, & Tah, 2017a). This allows data to be standardized and structured, providing a common basis for the various parties involved in a project. In (Staub-French, Fischer, Kunz, Ishii, & Paulson, 2003a), 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 Tableau 3.1). In (Xinghua Gao, Pishdad-Bozorgi, Shelden, & Tang, 2020a), 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 (Zhang, Li, Zhao, & Ren, 2018), 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 CO₂ 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. (Ghose, Lissandrini, Hansen, & Weidema, 2022) 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 (El-Diraby, 2005, 2006). 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 (El-Diraby, 2005), 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.

Tableau 3.1 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	(Xinghua Gao et al., 2020a)
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	(Zhang et al., 2018)

Tableau 3.1 Overview of WLC-related existing ontologies (suite)

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	(Ghose et al., 2022)
LCC Core model	OWL-based LCC schema; integrates costs and influencing factors; service-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	(El-Diraby, 2005, 2006)

3.4 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 (Dresch et al., 2015a). The foundational problem identified is the underutilization of the WLC approach in building projects due to inefficient heterogeneous 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 (Nguyen et al., 2019), 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 (A. R. Hevner, 2007a). The ODSR research framework of the present study is presented in Figure 3.1.

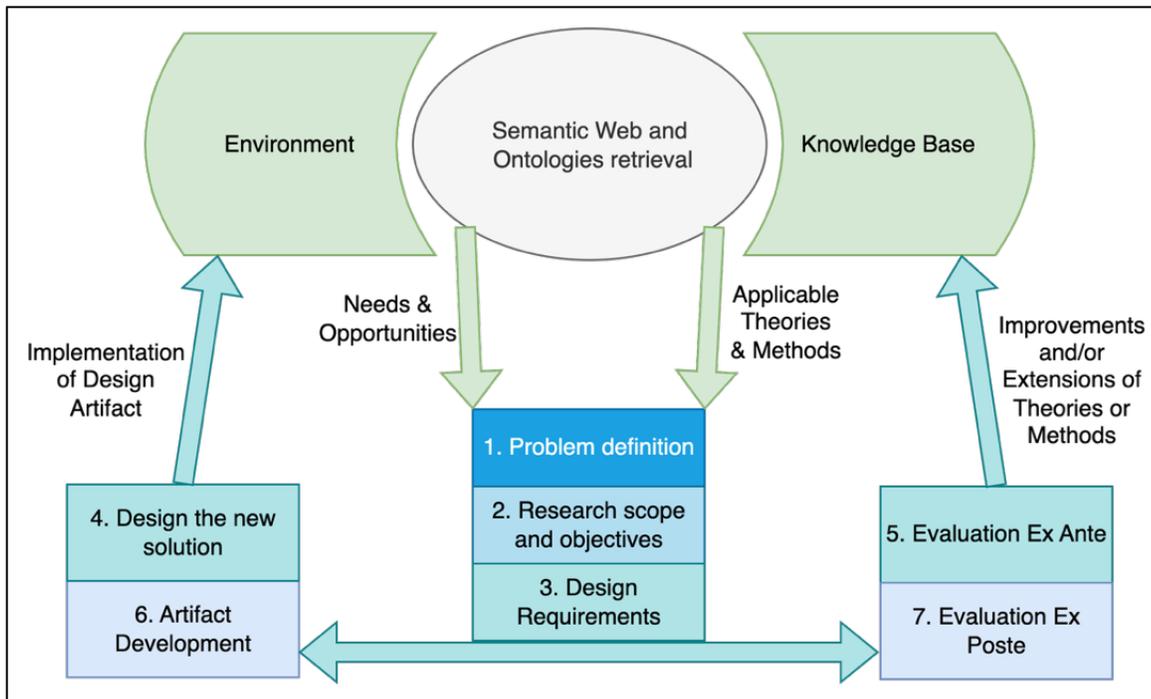


Figure 3.1 ODSR artifact development framework
Adapted from Hevner (2007)

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?

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 (Dresch et al., 2015a).

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 (Suárez-Figueroa et al., 2012a). 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.

3.5 Results

3.5.1 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 Tableau 3.2, 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.”

Tableau 3.2 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%

Tableau 3.2 Survey 1—Online questionnaire (suite)

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 Tableau 3.3. 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.

Tableau 3.3 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%

Tableau 3.3 Survey 2 results—Real-time questionnaire (suite)

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%

3.5.2 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?

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.

3.5.3 Design Requirements

3.5.3.1 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 Tableau 3.4.

Tableau 3.4 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	<p>Non-functional requirements: The ontology must be based on existing norms (ISO 15686-5, ISO 19650) and be flexible.</p> <p>Functional requirements (competency questions (CQs)) and their answers, as follows:</p> <p>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 15686-5)</p> <p>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.</p> <p>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.</p> <p>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.</p> <p>What are the expected costs at a specific time? Costs arising at the specific time of a project.</p>
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

3.5.4 Design of the New Solution

3.5.4.1 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 Figure 3.2 and Figure 3.3.

The standard presents, in Figure 3.3, 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) (Kishk et al., 2003). For the costs to be considered, as Figure 3.2 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.

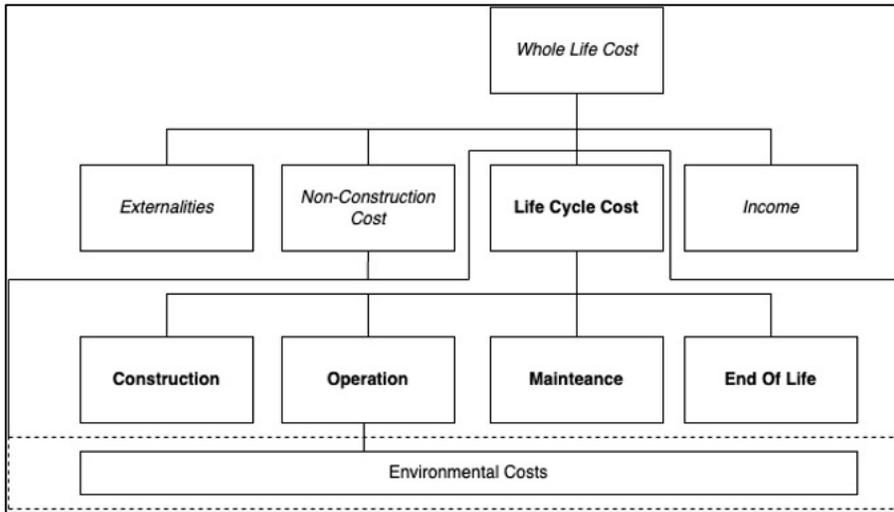


Figure 3.2 Conceptual schema
Adapted with permission from (ISO, 2017)

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, ceiling tiles, floor coverings, door fittings, etc.	All levels	
System level	Foundations, sold or framed wall and floors	Cladding, roofing, windows and doors	Energy, ventilation, water capacity. communications etc.	Wall, floor and ceiling finishes		Considerations: Costs Functions Maintenance Environment Disposal
Strategic level	Safety and durability	Location and external environment	Comfort and use	Maintainability and Internal environment		Life Cycle Stages: Planning Construction Operation Maintenance End-of-life

Figure 3.3 Conceptual schema
Adapted with permission from (ISO, 2017)

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 3.4.

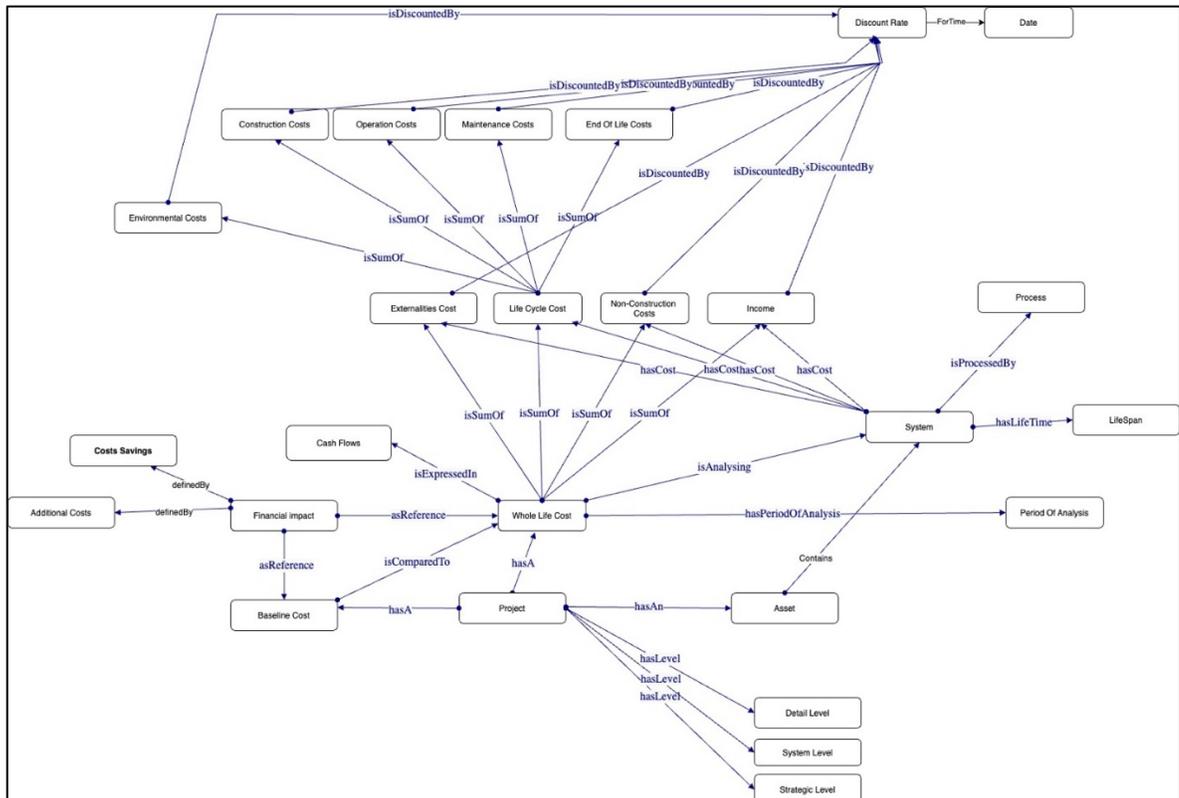


Figure 3.4 WLC consolidated conceptual model
Adapted with permission from (ISO, 2017)

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 Tableau 3.5, Tableau 3.6 and Tableau 3.7.

Tableau 3.5 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.

Tableau 3.6 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

Tableau 3.7 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.	Discounted Costs	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.	WholeLife Costs	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 (3.1):

$$Discounted\ Cost = \frac{C_n}{(1 + d)^n} \quad (3.1)$$

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 3.5, and the schematic representation of the main concepts of the ontology is represented in Figure 3.6.

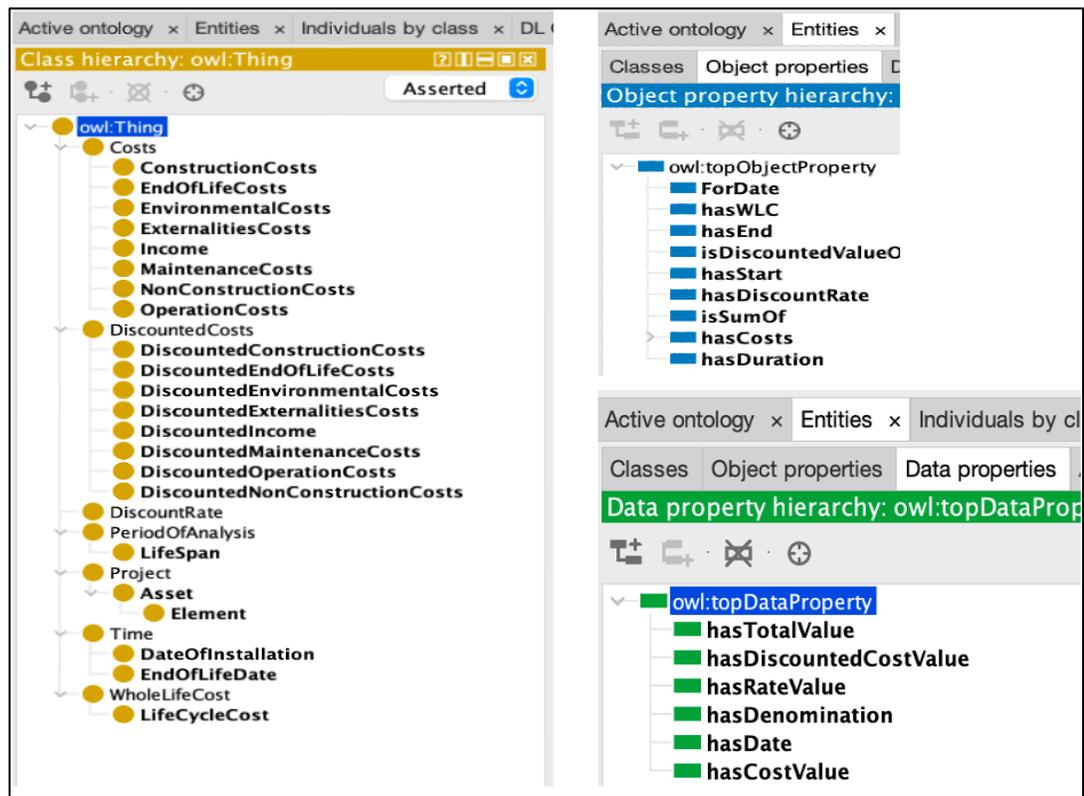


Figure 3.5 Classes, object properties and data properties in the Protégé software 5.6.5

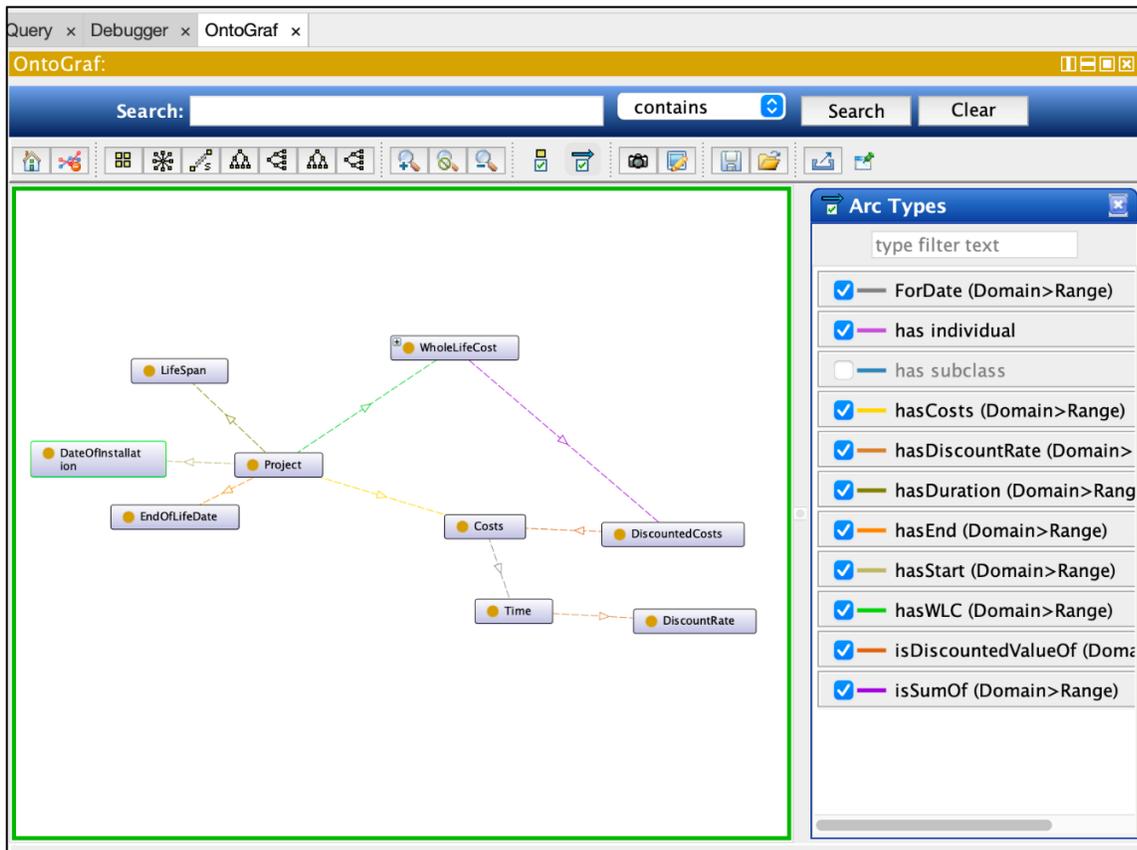


Figure 3.6 Schematic representation of the ontology from the ontology Protégé software 5.6.5

3.5.5 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 (Sabou & Fernandez, 2012). 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 3.7).



Figure 3.7: 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 3.8).

c	value	year	R
Maintenance2	800	:Year2	4
Op2	200	:Year2	4
Maintenance1	800	:Year1	3
Maintenance3	800	:Year3	5
Op1	200	:Year1	3
Maintenance4	800	:Year4	4.5
Op4	500	:Year4	4.5
NCdemolition	500	:Year5	4
ghg3	225	:Year3	5
ghg2	200	:Year2	4
ghg1	125	:Year1	3
ghg4	225	:Year4	4.5
ghg5	300	:Year5	4
NC1	1500	:Year1	3
ElectricityE	1200	:Year5	4

Figure 3.8 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 3.9) and the results (Figure 3.10).

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, Discount Rate, 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.

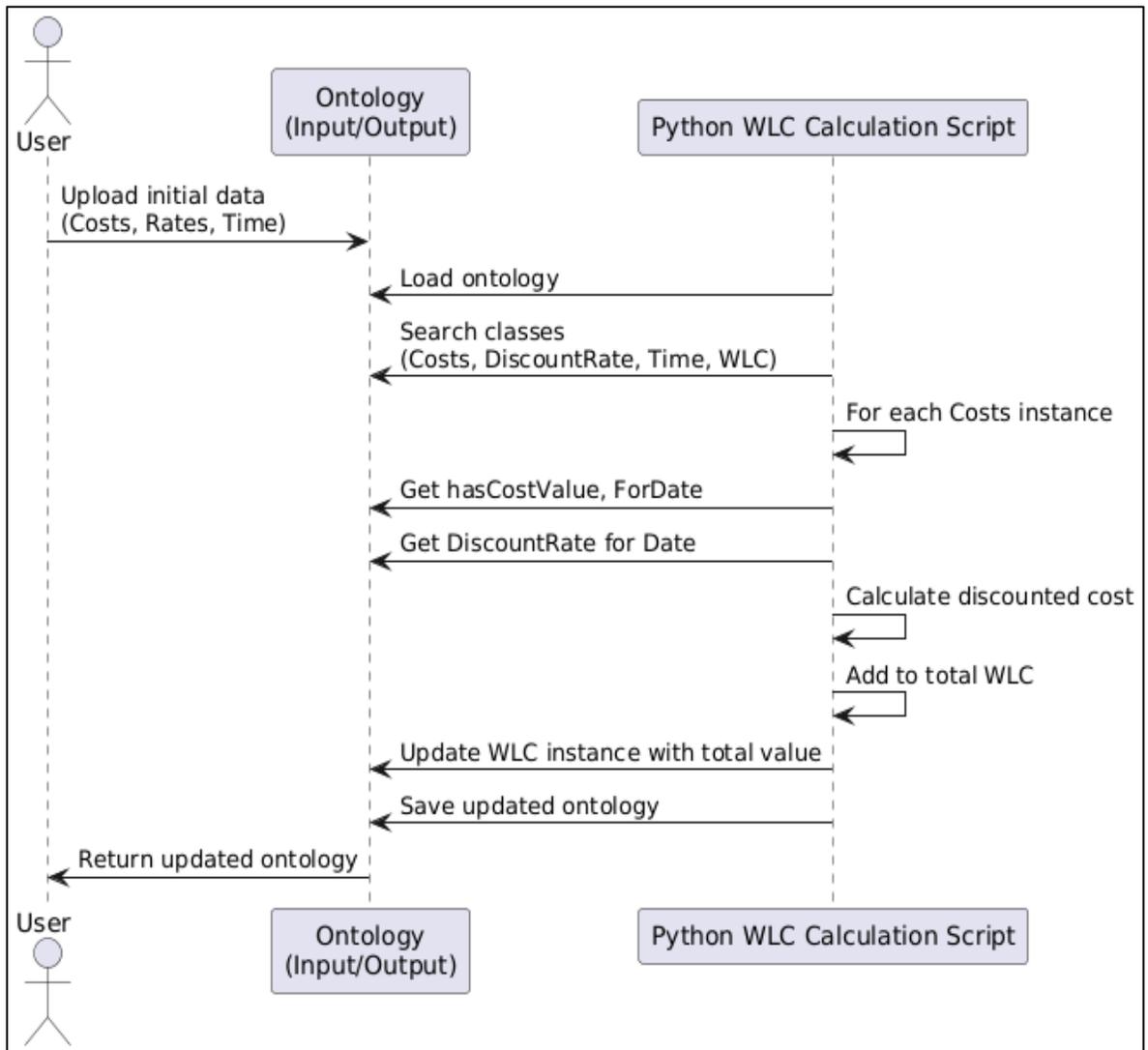


Figure 3.9 Python script for WLC calculation into the ontology

The image shows a terminal window at the top with the following log output:

```
[INFO] Chargement de l'ontologie depuis : /Users/adamyousfi/Downloads/cgontologie1.rdf...
[SUCCESS] Ontologie chargée avec succès !
[DEBUG] Recherche des classes pertinentes...
[INFO] Parcours des instances de 'Costs'...
[DEBUG] Traitement de l'instance cgontologie1.Asset_Construction...
[INFO] Coût actualisé pour cgontologie1.Asset_Construction: 5000.00
[DEBUG] Traitement de l'instance cgontologie1.Demolition...
[INFO] Coût actualisé pour cgontologie1.Demolition: 2465.78
...
[INFO] Whole Life Cost calculé et assigné 6909.41
```

Below the terminal is a screenshot of a web browser displaying the 'WholeLifeCost' ontology in a Semantic Web Editor. The browser address bar shows 'WLCONTO (http://www.semanticweb.org/adamy/ontologies/2025/WLCONTO)'. The interface includes a class hierarchy on the left, a description of the 'WLC' class, and a list of property assertions. A red box highlights the assertion 'hasTotalValue 6909.414440220575' in the 'Property assertions: WLC' section.

Figure 3.10 WLC calculation and integration of the result into the ontology

3.5.6 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 (Rasmussen et al., 2021). 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 3.11.

Figure 3.12 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.

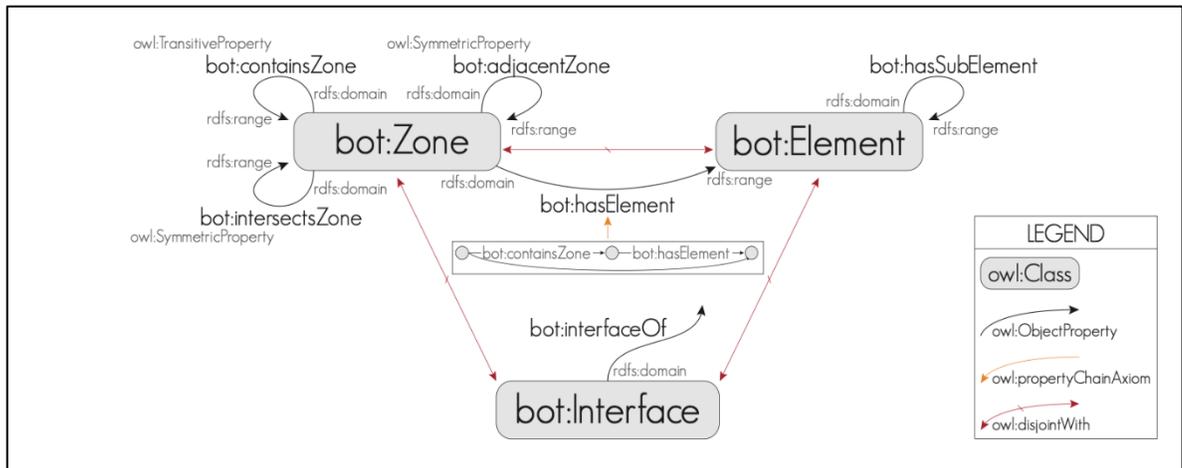


Figure 3.11 BOT structure
From Rasmussen (2021, p.149)

The screenshot displays an ontology alignment interface. On the left, a class hierarchy is shown with 'Site' highlighted. The right panel shows 'Property assertions: Land' with object property assertions 'hasCosts SiteCleaning' and 'hasCosts SiteWorks'. Below this, a table lists instances of 'Land' with their associated costs and categories.

p	c	value	discountedCost	Y
autogen0:AssetTest	autogen0:Demolition	3000.0	2465.8	5
autogen0:AssetTest	autogen0:Asset_Construction	5000.0	5000.0	0
bot:Land	bot:SiteCleaning	500.0	411.0	5
bot:Land	bot:SiteWorks	1000.0	1000.0	0

Figure 3.12 Ontology alignment with the BOT ontology

The figure shows the individual “Land” classified under Site (Zone). Translation: Éléments 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, proving 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 3.13).

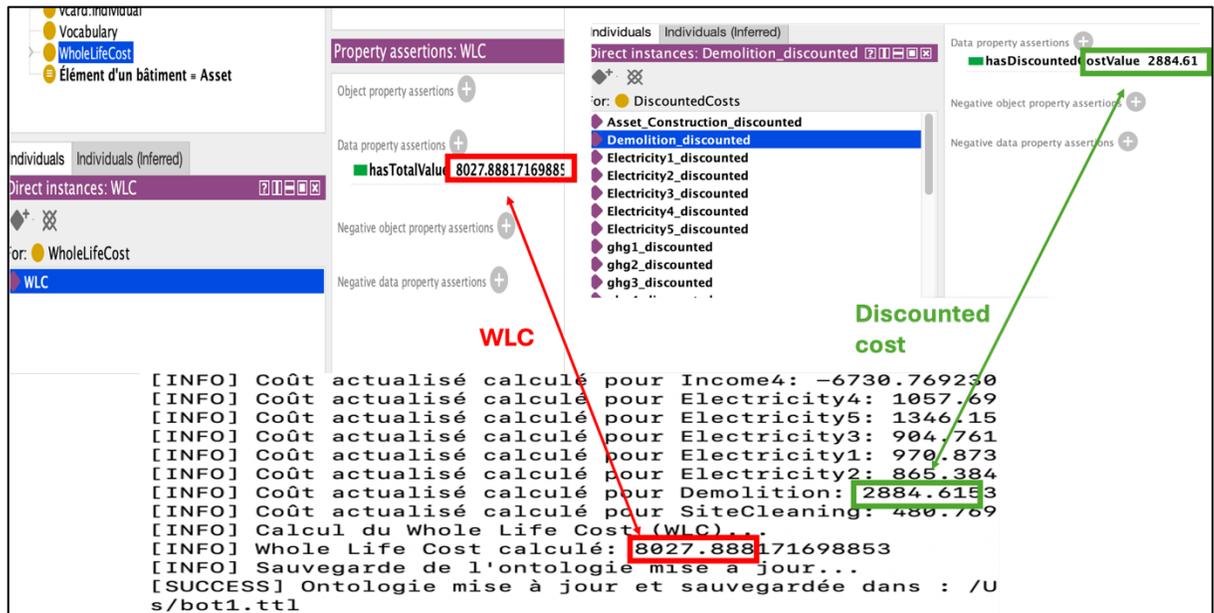


Figure 3.13 Integration of WLC results in the extended ontology

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.

3.6 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

(Tableau 3.4) 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 (El-Diraby, 2006). 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 WLCONT0 presented here modeled 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.

3.7 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 (Nguyen et al., 2019), 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.

Author Contributions:

Conceptualization, A.Y.; methodology, A.Y.; software, A.Y.; validation, A.Y., É.A.P. and D.F.; formal analysis, A.Y.; investigation, A.Y.; resources, É.A.P. and D.F.; data curation, A.Y.; writing—original draft preparation, A.Y.; writing—review and editing, A.Y.; visualization, A.Y.; supervision, É.A.P. and D.F.; project administration, A.Y., É.A.P. and D.F.; funding acquisition, É.A.P. and D.F. All authors have read and agreed to the published version of the manuscript.

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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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CHAPITRE 4

DYNAMIC WHOLE LIFE COSTING ANALYSIS THROUGH A KNOWLEDGE-GRAPH DATABASE

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4.1 Abstract

The increasing complexity of construction projects and the growing need for sustainability have shed light on the importance of Whole Life Costing (WLC) as a decision-support method. While Building Information Modelling (BIM) and complimentary digital technologies have improved data management and automation, WLC analysis remains limited by fragmented and heterogeneous data sources. This study proposes an ontology-driven WLC platform implemented within an RDF-based Knowledge Graph Database (KGDB) to operationalise WLC as a dynamic, project-level decision-support system. The platform enables the semantic integration of BIM data, cost estimations, and temporal parameters, and supports automated aggregation, querying, and WLC computation. Using a Design Science Research methodology, the artefact is designed, implemented, and evaluated through a building case study involving the comparison of alternative design scenarios. The results demonstrate that the proposed KGDB-based approach supports continuous data integration, automated WLC computation, and scenario-based analysis, facilitating early-stage cost-informed decision-making. By treating WLC as an incremental and iterative process rather than a static post-design evaluation one, this work highlights the potential of

KGDB to bridge the gap between semantic modelling and practical cost engineering workflows.

4.2 Introduction

The evolving requirements underlying the delivery of sustainable built assets introduce new layers of complexity for design and cost management teams. Cost engineers face increasing pressure to predict long-term financial implications and ensure cost control across the entire project lifecycle (Fuller, 2010). Estimation inaccuracies can lead to credibility loss, increased risks, and financial instability (Awosina, Ndiokubwayo, & Fapohunda, 2018). As projects become more complex, cost estimation has evolved into a strategic discipline requiring not only technical and analytical skills but also an active contribution to constructability, design optimization, and project planning (Alleman, Duval, & Molenaar, 2017).

Among strategies supporting sustainable cost-based decision-making, Whole Life Costing (WLC) can help identify the most cost-effective project alternatives by thoroughly evaluating all relevant costs throughout an asset's lifespan (Heralova, 2014). WLC helps to structure a shared understanding of costs throughout the life cycle of an asset, and can expose hidden or unanticipated costs from multiple stakeholder perspectives (Caniato, 2014). By promoting transparency pertaining to economic challenges faced by each of the parties involved, WLC facilitates the negotiation and cooperation of stakeholders. Consequently, its shared use can foster a strengthened level of trust and collaboration among them (Zachariassen & Arlbjørn, 2011). However, its implementation is often hindered by the lack of standardized methodologies and challenges in data acquisition (Olubodun et al., 2010). WLC consumes significant amounts of data, and its accuracy depends on its quality and availability across all project phases. Essential data for estimation is often scattered and heterogeneous, stored in various unstructured or semi-structured containers such as spreadsheets, documents, or 3D models (Cassandro, Mirarchi, Zanchetta, & Pavan, 2024). Therefore, data can be structured or unstructured, sourced from historical projects, actual modelling or from suppliers and subcontractors (Zanni, Sharpe, Lammers, Arnold, & Pickard, 2019). In practice, the lack of

structured mechanisms to integrate, align, and update these heterogeneous data sources remains a major barrier to the operational use of WLC in real projects.

Yet, despite the increasing availability of data, the construction sector remains one of the least digitised industries (Shen, Sepasgozar, & Ostwald, 2024), and decision-making processes continue to rely heavily on fragmented and analogous information flows. In a context where governments and clients demand greater accountability for the environmental and financial performance of projects, the ability to access and analyse life-cycle cost data has become a strategic requirement (Shaw et al., 2025). In this context, cost engineers are expected to play a leading role in multi-stakeholder environments, supporting collaborative and informed decision-making (Farr & Faber, 2018 ; Fuller, 2010). In practice, cost estimation processes remain highly fragmented. Early design estimations are typically based on disparate sources of data and rely heavily on expert judgment and heuristics. Traditional approaches limit the ability to perform continuous and transparent cost analysis throughout the project lifecycle. Indeed, the heterogeneity of data make manual collection, integration, and alignment complex, time-consuming, and error prone. In addition, even data sources that are considered interoperable, such as IFC models or comma separated values , often prove to be incomplete to achieve a full WLC analysis. They frequently lack specific data, such as the exact costs of replacements or the maintenance frequencies associated with components, requiring manual completion efforts (Zanni et al., 2019). Bridging the design and operational phases is essential for improving the reliability of long-term cost predictions. However, most tools and methodologies used by cost engineers focus on short-term or phase-specific cost estimations, lacking a dynamic link with actual lifecycle performance and a broader, encompassing, whole lifecycle perspective. As a result, cost engineers lack the necessary systems and processes that support both WLC analysis and dynamic scenario exploration.

To address these challenges, several studies have explored Building Information Modelling (BIM)-based approaches to enhance WLC analysis. BIM has demonstrated its ability to improve data accessibility, automate quantity take-offs, and facilitate simulations during early design stages (Muhammad Altaf et al., 2020). Effective approaches exposed in the

literature propose diverse integrations of BIM for robust WLC analyses. BIM can serve as a central repository to systematically extract material quantities, life-cycle data, and sustainability parameters, which can then be used in risk simulations to optimize WLC considering economic, environmental, and risk factors (Mohamed Marzouk, Azab, & Metawie, 2018). BIM platforms can automate quantity extraction and streamline WLC calculations within dedicated software environments, allowing flexibility for user-defined adjustments (Kehily & Underwood, 2017). Another promising approach involves embedding WLC calculations and Life Cycle Assessment (LCA) directly within BIM tools, thereby significantly reducing potential errors related to manual data handling and enhancing automation and access to necessary project data (Santos, Aguiar Costa, et al., 2020). However, these methods often remain tool-specific and lack the semantic flexibility needed to integrate data from heterogeneous sources and contexts. Despite improved interoperability, current BIM-centric workflows do not provide an interoperable semantic framework capable of connecting and reasoning across all types of data required for a comprehensive WLC analysis. Also, BIM models, while rich in geometric and quantitative information, remain limited in their ability to represent the contextual meaning of data. BIM standards such as IFC define a shared data schema, but the lack of explicit formal semantics limits their ability to support automated reasoning and integrated analyses (Zhou et al., 2022). As a result, BIM-based WLC approaches often fail to capture the relationships between cost data, lifecycle stages, and decision variables, making it difficult to perform automated or dynamic analyses. As digitalisation progresses, cost engineers must not only access data but also interpret, adapt, and simulate scenarios in real time. Static databases and tool-specific models are no longer sufficient. This limitation has led to an increasing interest in semantic web technologies, which aim to add meaning, logic, and reasoning to data (Boje, Guerriero, Kubicki, & Rezgui, 2020).

Recent advances in semantic web technologies offer new opportunities to overcome this fragmentation (Shen et al., 2024). Ontologies and Knowledge Graphs (KG) enable semantic interoperability and structured data exchange. Their use has been shown to improve data integration, and support knowledge-based decision-making (Pauwels & Terkaj, 2016).

Leveraging KGs as Data Bases for information management, the development of Knowledge Graph Databases (KGDBs) enables the dynamic storage, querying, and reasoning of semantic data. They provide a scalable infrastructure where both structured and unstructured data can be connected, updated, and processed through query languages such as SPARQL (B. Liu et al., 2021). In the AEC sector, KGDBs offer a unique opportunity to merge ontological reasoning with data operations, enabling real-time interaction between cost models, design parameters, and lifecycle indicators (Shaw et al., 2025). This would make them particularly suited to bridge the gap between static semantic models and the practical needs of WLC computation and decision support. However, few studies have demonstrated how such semantic infrastructures can be concretely operationalised to support WLC computation and design-stage decision-making.

The study presented in this paper aimed to operationalise WLC through a semantic platform implemented within a KGDB. The proposed framework enables the integration of distributed and heterogeneous data, supports reasoning over cost relationships, and facilitates collaboration between cost engineers and project stakeholders. The paper demonstrates how a KGDB can be used to support dynamic WLC computation, scenario comparison, and collaborative analysis, bridging the gap between conceptual semantic modelling and real-world project decision-making. The development of this semantic platform follows a Design Science Research (DSR) approach. The artifact builds upon a core ontology grounded in the ISO 15686-5 standard that provides a formal conceptualization of WLC concepts, cost structures, and temporal attributes (Adam Yousfi, Poirier, & Forgues, 2025). It is implemented and tested through a case study in the building sector, focusing on the integration of heterogeneous cost data sources and the validation of dynamic WLC computations. Through this applied perspective, the research aims to contribute not only to the theoretical advancement of semantic modelling for WLC but also to the digital transformation of cost engineering practices.

The article is structured as follows: Section 2 introduces the WLC basics and delves into the management of heterogeneous data in the construction and application of ontologies and

knowledge graphs. Section 3 details the research methodology adopted for this study, based on the DSR framework, which guided the identification of problems, the development of the artifact and its evaluation. Section 4 describes the design of the used ontology and the technical architecture of the platform developed. Section 5 presents the implementation of the platform and demonstrates its ability to address the challenges identified through a case study. Section 6 discusses the results obtained, assesses the contributions of the research in relation to the original objectives, discusses the limitations of the approach and explores the implications for research and practice. Finally, Section 7 concludes the study by highlighting the main contributions of this work and proposing future research perspectives.

4.3 Literature review

4.3.1 Whole Life Costing

Comprehensive economic evaluations aiming at improving resource allocation by implementing cost-effective solutions are mainly ensured by domains such as building economics, value engineering, and cost engineering (Fuller, 2010). Various methods can serve to measure economic efficiency throughout a project's life. WLC, along with measures like Payback Period (PB), Internal Rate of Return (IRR), Net Savings (NS), and Savings-to-Investment Ratio (SIR), are specifically used to assess long-term ownership costs by considering all costs incurred from conception to disposal (Farr & Faber, 2018 ; Fuller, 2010). WLC is particularly valued by estimators and financial experts because it informs investment choices by capturing the relevant cost implications associated with each decision throughout an asset's lifecycle. The approach is guided by ISO 15686-5:2017 (ISO, 2017), which defines an asset's whole life cost as *“all significant and relevant initial and future costs and benefits of an asset, throughout its life cycle, while fulfilling the performance requirements”*. As stated in this standard, the role of WLC is to quantify life cycle costs to support a decision-making or evaluation process. By enabling detailed financial comparisons of product lifespans and associated replacement cycles, WLC assists practitioners in identifying products or solutions that optimize the useful life of assets (Mistry et al., 2016). In addition, its methodological flexibility allows practitioners to perform sensitivity analyses

to assess how different economic scenarios may affect cost evolution and risk exposure (Wieczorek, Plebankiewicz, & Zima, 2019). As highlighted by Pearce (Pearce et al., 2010), WLC can also be understood as a collaborative framework, where cost performance emerges from the interactions between users, institutions, technologies, and environmental contexts. In this sense, WLC inherently supports integrated decision-making by aligning the financial perspectives of multiple stakeholders around long-term value creation. Nevertheless, practitioners often face barriers in fully realizing WLC's potential due to data fragmentation, methodological inconsistencies, and a lack of flexible tools for long term decisions (Cole & Sterner, 2000 ; Roda et al., 2020 ; Soust-Verdaguer et al., 2017). This gap highlights the need for more collaborative and data-driven tools to make WLC analysis attractive.

4.3.2 Ontologies and knowledge graphs in the construction industry

4.3.2.1 Semantic Representation and Data Interoperability in Construction

Efforts within the construction industry to improve its effective digitization are rapidly evolving. Interoperability of BIM models through open data formats such as IFC succeeds in facilitating data exchange. However, these formats lack contextual semantic definitions and remains static, which limits the potential for automatic analysis based on machine reasoning (Zhou, 2022). In this context, the emergence of semantic web technologies offers promising ways to structure, integrate, and use complex data in this sector. These technologies aim to turn information into a network of interconnected knowledge, making it easier to find, understand, and use data (Patel & Jain, 2021). The application of these technologies in the construction sector began in the early 2000s, with a marked interest in the integration and management of heterogeneous data from different sources in order to improve research and access to information (Shen et al., 2024). In line with the foundations of the Semantic Web, these approaches use ontologies to formalize the concepts and relationships of a domain, making data understandable and interoperable (Patel & Jain, 2021 ; Shen et al., 2024).

In the domain of Information Sciences, an ontology is a machine-readable representation of knowledge about a concept or object. It structures and connects data for use by humans and

machines (Berners-Lee & Hendler, 2001). The role of ontologies is to provide a foundation for constructing models of all aspects of computer science (Mizoguchi & Ikeda, 1998). Ontology has emerged as a key solution for structuring and linking heterogeneous data in the construction sector, particularly through standards like RDF, OWL, and SPARQL (Pauwels et al., 2017). It enables semantic data integration by representing both data and their relationships conceptually, thus supporting more automated and contextualized information management (Niknam & Karshenas, 2017b).

Ontologies such as the Building Topology Ontology (BOT) (Rasmussen et al., 2021), the Digital Construction (DiCon) ontology (Zheng et al., 2021), and the ifcOWL ontology (Pauwels et al., 2017) have been developed to formalize the description of buildings, construction processes, and BIM data using semantic web technologies. These ontologies serve as the foundation for domain-specific extensions, allowing for more effective data unification, especially in multidisciplinary and collaborative contexts (Domingue, Fensel, & Hendler, 2011b).

Ontologies have been increasingly applied in construction cost estimation for their capacity to support the integration of heterogeneous data sources, structure complex information, and enable automation. Several studies have shown that the use of ontologies can improve quantity take-off and cost accuracy by enabling rule-based reasoning and standardizing information from BIM models and technical documents (H. Liu et al., 2016 ; Ma, Liu, & Wei, 2016). They also allow for the incorporation of established measurement standards to ensure consistent calculations across stakeholders (Abanda, Kamsu-Foguem, & Tah, 2017b). In some cases, ontologies have been used to model design functionalities directly influencing costs, supporting more adaptive and feature-based estimation workflows (Staub–French, Fischer, Kunz, Ishii, & Paulson, 2003b). Ontologies alone remain at a conceptual level as they define the structure of knowledge without supporting its direct instantiation or operational use. To make these models actionable and link them to real project data, recent research has increasingly relied on KGs, which instantiate ontological concepts and enable data-level reasoning and analysis (Patel & Jain, 2021 ; Shen et al., 2024). Transforming these

conceptual models into KGs enables their connection with real project data and supports reasoning, querying, and dynamic analysis within applied contexts (Patel & Jain, 2021 ; Shen et al., 2024).

4.3.2.2 Knowledge-based environment application

KGs can be considered as instantiations of ontologies. While ontologies provide a formal schema for structuring domain concepts and their relationships, knowledge graphs populate these models with data, leveraging the reasoning, integration and querying for different use cases (Dibowski & Schmid, 2021 ; Pileggi, 2022). Unlike traditional databases, KGDB can serve to unify diverse data formats, support advanced querying, inferencing, and knowledge discovery (Yan, Wang, Cheng, Gao, & Zhou, 2018). More recently, KGDB have also gained traction in artificial intelligence (AI) research, where they serve as foundational structures for graph-based learning, semantic search, and knowledge enrichment (Peng, Xia, Naseriparsa, & Osborne, 2023). The operational approach of KGDB follows the Ontology-Based Data Access (OBDA) principle, focusing on accessing data through the ontological layer (Corcho, Priyatna, & Chaves-Fraga, 2020). Materialisation and virtualisation techniques are options to manage ontology-data interaction. Materialisation transforms data into an ontology-aligned representation, while virtualisation translates ontology queries into native data system queries. Virtualisation emerged within OBDA as a thorough solution to avoid the need for physical data duplication, offering advantages particularly for dynamic sources and efficient querying over large datasets without over-storage (Corcho et al., 2020 ; Mercier et al., 2018). Adopting an ontology-driven approach is particularly suitable for the construction domain, where data heterogeneity remain persistent obstacles (Mercier et al., 2018). The emergence of KGDBs offers a unified infrastructure to connect semantic reasoning with operational data management, creating new opportunities for dynamic analysis and cross-domain interoperability in AEC projects.

While most semantic approaches rely on RDF-based triple stores, other graph paradigms such as Label Property Graphs (LPG) have also been adopted in construction research for

their flexibility and performance, notably in applications such as the LCAIM framework by Shaw (2025). However, LPGs lack the formal semantics necessary for logical reasoning and ontology alignment (B. Liu et al., 2021). In contrast, RDF-based models are explicitly designed for ontology representation and reasoning within the semantic web ecosystem, following established W3C standards such as RDF, RDFS, and OWL (Patel & Jain, 2021), which makes them particularly appropriate for life-cycle knowledge structuring and inference. Furthermore, unlike LPGs implementation, which require external scripts to compute or update analytical results, RDF graph databases such as GraphDB natively support SPARQL 1.1 operations. This enables both querying and direct graph updates (W3C, 2013), ensuring continuous synchronization between data, reasoning and visualization layers.

Shen (2024) proposes a structured vision of the Semantic Web, illustrating how raw data is gradually transformed into usable knowledge through several interdependent layers:

- Resource data layer: Collects and prepares information from different sources, such as texts, databases, sensors, or BIM models.
- Modeling layer: Formalizes this data using RDF structures and ontological languages such as RDFS or OWL, in order to give it explicit meaning and semantic interoperability.
- Reasoning and validation layer: Applies logical mechanisms to check data consistency and deduce new relationships between concepts.
- Application layer: Leads to the creation of knowledge graphs, which are networks of interconnected information enabling advanced data querying, integration, and analysis.

Knowledge graphs are promising solutions that leverage a structured knowledge framework to optimize information management, making data accessible and meaningful for a variety of use cases.

4.3.3 Application for WLC

Despite increasing interest in developing tools facilitating the use of WLC in practice, its application through knowledge-based environment has not been addressed in the literature.

Most studies focused on data integration or specific applications, such as facility analysis (Xinghua Gao, Pishdad-Bozorgi, Shelden, & Tang, 2020b), sustainability-based design (Zhang et al., 2018), or environmental flows (Ghose et al., 2022), without modeling the full WLC methodology. El-Diraby (2006) proposed a comprehensive ontology framework, but focuses on the LCC scope and predates current BIM-based workflows. More recently, Shaw (2025) proposed the Life Cycle Asset Information Management (LCAIM) ontology and its associated KGDB to operationalise WLC within policy- and practice-aligned reporting frameworks. Their implementation applies WLC at the asset level, with the ontology supporting aggregation from components to whole facilities. The system integrates and structures the required technical and financial data, which are externally processed through Python scripts to compute discounted costs and scenario comparisons, before being reinserted into the graph for enhanced querying, traceability, and reporting. While this work represents an important step toward WLC operationalisation using semantic web technologies, its emphasis remains on information traceability and regulatory compliance rather than on design-stage decision support. Namely, it fails to address the question of how WLC can be appropriated and collaboratively used by project stakeholders during early design stages, when cost-informed decisions have the greatest impact on long-term performance in a KGDB environment. To this effect, KGDBs have rarely been applied to WLC computation or integration with design stage data such as BIM models or cost estimation spreadsheets. Consequently, there remains limited evidence of how KGDB can combine reasoning functionality, computational processing, and project-level usability within a design workflow. Building upon this gap, the present research complements the governance-oriented perspective of Shaw (2025), by addressing the early design phase, where cost estimators and engineers must simulate and compare life-cycle alternatives under uncertainty.

The following section details the methodology adopted to structure and implement this ontology-driven framework, outlining the design process, underlying standards, and integration mechanisms that enable its practical use within current construction workflows.

4.4 Methodology

The purpose of the paper is to demonstrate how a KGDB can be used to support dynamic WLC computation, scenario comparison, and collaborative analysis. This work is part of a larger study, conducted using a DSR approach. DSR is an iterative methodology aiming at generating new knowledge and artifacts that will answer a practical problem (Dresch et al., 2015a). In the realm of Information Technology, artifacts produced through DSR encompass constructs that serve as representations of vocabulary and symbols, models that encapsulate abstractions and representations, methodologies that propose algorithms and practices, and instantiations that represent solutions that have been implemented and prototype systems (A. Hevner & Chatterjee, 2010). This study presents a new cycle to this work by proposing the instantiation phase of a previously developed core WLC ontology (Yousfi et al., 2025). The steps of the design science methodology as proposed in (Dresch et al., 2015a), have been adapted in this research to implement a continuous validation process toward the artifact, as suggested in (Sonnenberg & vom Brocke, 2012). In addition, this study builds upon the methodological structure underscored by Shen (2024), who reviewed a set of comparable studies and identified four recurring stages in the implementation of semantic web technologies: ontology and knowledge graph establishment, data and knowledge sourcing, knowledge querying, and model validation and evaluation. In line with this positioning, the methodological steps are structured in such a way as to support the instantiation of the artefact while allowing for its progressive validation. The contribution of this study lies in the operationalisation of a previously developed WLC model through a semantic platform. The methodology and application do not aim to redefine WLC principles, but to ensure that the proposed instantiation remains theoretically sound, relevant to cost engineering practices, and technically consistent. Thus, evaluation activities are integrated into different stages of the DSR process, following a logic of continuous validation, to successively compare the artefact with the state of the art, domain expertise and its implementation. This approach allows the artefact to be optimised throughout its development rather than evaluating it only after its construction. The steps followed are showed in the Figure 4.1 and described below.

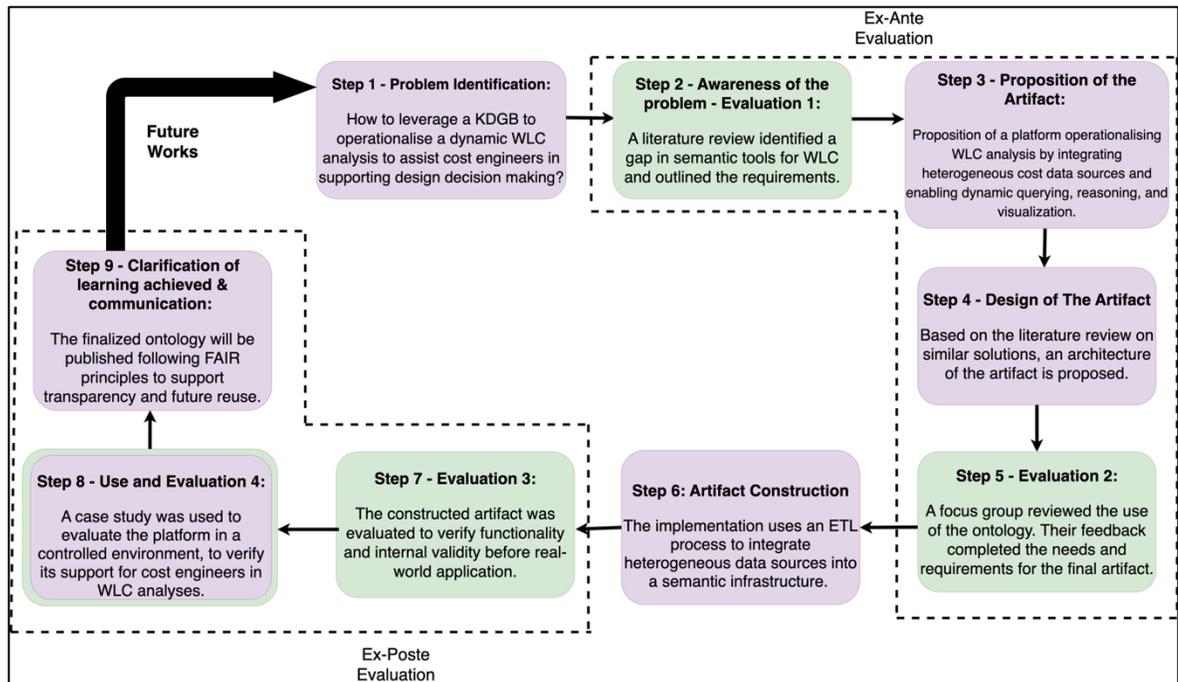


Figure 4.1 Methodological Framework

Adapted from (Sonnenberg & vom Brocke, 2012)

The first step of DSR aims the research problem identification. The primary motivation behind the broader work of which this study is a part, is to leverage new information technologies to operationalise WLC and encourage its adoption within the built asset industry. This objective requires exploration of both the technological and the cultural aspects of a new WLC solution integration. Cultural and practical aspects were explored elsewhere, highlighting the need for cost engineers to take the lead of WLC adoption and proposing solutions to make it common practice. This paper focuses on the technological aspects, in a context where simple BIM-based solutions are not enough to anchor the WLC in practices. Hence, semantic web technologies are explored to build robust WLC solutions to support cost engineers. Accordingly, the present work supports the operationalisation of a dynamic WLC analysis to assist cost engineers in supporting design decision making by leveraging KDGB technologies.

The subsequent steps correspond to an Ex-Ante evaluation phase, in which the artifact is progressively defined and validated before its implementation. As supported in (Sonnenberg

& vom Brocke, 2012), the first evaluation process aims at confronting the problem identified through the literature review, establishing the theoretical relevance of the proposed artifact. The previous section has established that, although some studies have advanced semantic approaches for cost and asset management, a gap persists in the identification solutions for an operational WLC integration within design workflows. No existing solution currently demonstrates how a KGDB can embed WLC computation and reasoning into project design decision-making.

Following this positioning, the proposed artifact was developed, building upon a core ontology aligned with ISO 15686-5 (Yousfi et al., 2025) and extending it into a semantic platform implemented within a KGDB. This platform operationalises WLC analysis by integrating heterogeneous data sources and enabling dynamic querying, reasoning, and visualization. Its objective is to provide cost engineers with a unified and interoperable environment to simulate, compare, and communicate life-cycle cost scenarios during the design phase, thereby supporting informed and collaborative decision-making.

The design of the artifact then focused on transforming the conceptual WLC ontology into an operational framework supporting a dynamic WLC analysis. The architecture is based on an RDF-graph implemented within a KGDB, providing semantic reasoning and querying capabilities through SPARQL. Following the OBDA paradigm, data remain in their original formats (BIM, spreadsheets, databases) and are accessed virtually through the ontology layer, avoiding duplication and enabling real-time integration of heterogeneous sources. The ontology captures the main WLC concepts and relationships aligned with ISO 15686-5, including cost categories, temporal attributes, and discount factors. These relationships allow the system to perform reasoning and automated alignment between data sources and life-cycle stages. Together, the RDF-based architecture and data virtualisation mechanisms provide the foundation for a dynamic WLC supporting design-stage decision-making.

The Ex-Ante evaluation ends with a second evaluation before the construction of the solution. A focus group, composed of five construction economists and estimators with

experience in WLC, was formed to reflect on the WLC-ontology based solution to define the right ontology specifications and functionalities of the platform. A focus group approach was selected to facilitate discussions among estimators about their practices and to propose a relevant solution. This approach aimed to mitigate researchers' biases and helped consolidate the ontology and choice of features for the platform designed based on the knowledge environment, ensuring representativeness with the field of application. This evaluation contributes to the domain validity of the artifact by confronting the artifact with established professional practices prior to implementation.

The artifact construction step was subsequently used, building on insights garnered in the previous steps. The implementation follows an Extract–Transform–Load (ETL) logic to operationalize the integration of heterogeneous data sources within the semantic infrastructure. Extraction begins when the user uploads a BIM model in IFC format and, optionally, related cost spreadsheets. The backend leverages the IfcOpenShell library to parse the model, identify entities, and extract relevant attributes such as GUIDs, classifications, materials, and quantities. Transformation is performed by serializing these extracted data into RDF triples, aligning them with the WLCONTO ontology classes and properties (e.g., `hasCostValue`, `hasDuration`, `hasUniformatCode`). This step ensures that design, temporal, and cost data are represented according to a unified semantic schema. Loading completes the process as the RDF triples are inserted into the KGDB via SPARQL INSERT and UPDATE queries. The GraphDB platform has been chosen to store the KGDB, which then performs automatic inference to classify instances and support subsequent reasoning and aggregation tasks. Through this ETL pipeline, all source data become semantically queryable within a consistent, ontology-based structure, enabling synchronization between BIM models, cost data, and computational analyses.

Following the construction of the artifact, an Ex-Post evaluation phase was performed, aimed at assessing the implemented solution. The constructed artifact was first assessed through a technical demonstration within a building project. This evaluation focused on verifying the artifact's internal consistency, reasoning capabilities, and ability to process heterogeneous

data through the KGDB. This evaluation corresponds to the demonstration evaluation pattern, which aims to verify the artifact's functionality and internal validity before its application in a realistic scenario (Sonnenberg & vom Brocke, 2012).

To achieve the final evaluation, a real-world scenario was used. This step focused on verifying how the ontology-driven framework and its computational mechanisms could support cost engineers in performing dynamic WLC analyses under realistic project conditions. Given the prototype's development stage, this evaluation was carried out in a controlled environment rather than a live project deployment, nevertheless aligning with the Artificial-Ex Post evaluation type (Pries-Heje et al., 2011).

Finally, this DSR cycle ends with the clarification of learning achieved & communication. In this final step, the discussion and conclusion are proposed to identify the theoretical and practical learnings. As part of this step, the finalized ontology was also be published following FAIR principles (Findable, Accessible, Interoperable, and Reusable), to support transparency, dissemination, and future reuse by both researchers and practitioners (Wilkinson et al., 2016).

The outcomes associated with each of these methodological steps are reported in the subsequent Results section.

4.5 Results

The results section first presents the outcome of Step 4 – Design of the artifact, as Steps 1 to 3 (problem identification, awareness, and solution proposal) were addressed in the previous sections. It then details the proposed platform, its main functionalities and processes, followed by the different evaluations conducted to validate the proposed artifact.

4.5.1 Designing the artifact

The present work is the continuity of a previous study which resulted in a WLC core ontology based on the ISO 15686-5 standards. The ontology, developed using Protégé, integrates cost categories, parameters, and temporal aspects for practical WLC calculations (Figure 4.2). The work developing this ontology demonstrate how to use it to perform calculations and structuring results solely through manual data entry into the instances of each class within the ontology. Hence, the present paper demonstrates the instantiation of this ontology (Adam Yousfi et al., 2025).

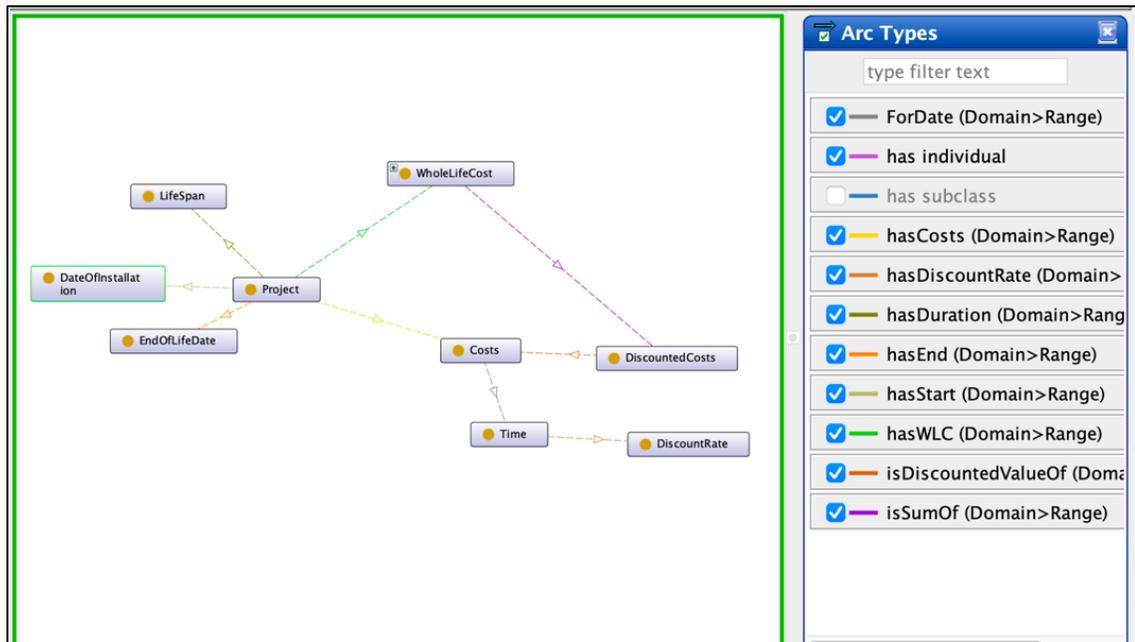


Figure 4.2 WLC core ontology

Following the design specifications defined in Step 4, the platform architecture was structured around an RDF-based Knowledge Graph within GraphDB (Ontotext, 2025), ensuring semantic interoperability and reasoning capabilities. In the best-case scenario, the user will have a complete IFC BIM model, with each element including all the WLC requirements. Unfortunately, today's practices are far from this ideal. Hence, to design the intended artifact, the data source that will feed the ontology must be defined to specify the

data format that will be used. WLC analysis described in the ISO15686-6 requires the building's physical information, quantities of elements, the different life cycle costs elements of the project, the life spans of each element of the building, the costs occurrence date, environmental impacts and their work and recovery costs, and the different scenarios of simulation as input. Considering the complexity of gathering these data, the present study proposes to first consider that the cost engineer carries out each phase estimation before analysing the whole life cost. Hence, the data requirements identified for this project are the project information, the phase cost estimations, the data about elements' life span, the discount rates and the period of analysis of the project. These data can be retrieved from BIM models, estimation spreadsheets, data bases or directly inputted manually. The project also favors an openBIM approach to promote interoperability and facilitate the widespread adoption of the approach. The data requirements are resumed in the Tableau 4.1.

Tableau 4.1 Data requirements

Data requirements	Data sources	Formats
Project information	BIM model	.ifc
Construction/ Operation/ Maintenance/ End of Life costs	Estimations or BIM models	.xlsx, .csv, .ifc
Temporal data: Discount Rate, period of analysis, Life spans data	Data bases, BIM models, Manual input	.xlsx, .csv, .ifc

As defined in Step 6 of the methodology, the data integration process follows an ETL logic. When the user uploads an IFC model, the backend parses its entities through the IfcOpenShell library, extracts key attributes, and serialises them into RDF triples aligned with the WLCONT0 ontology. These triples are then loaded into the KGDB (GraphDB) through SPARQL commands, ensuring full semantic alignment between BIM data and the ontology.

4.5.2 Evaluation n°2

A conceptual prototype of the artifact was presented to the focus group to illustrate the ontology's potential for integrating heterogeneous data. The objective of this evaluation was to validate the completeness of data requirements and ensure alignment between the ontology's conceptual scope and practitioners' expectations. The group discussed the concepts behind the application and expressed their expectations considering the possibilities of the future artifact. Required data were confirmed with the group to validate the identified requirements. The following data requirements were identified:

- Construction costs
- Energy consumption
- Building and elements lifespan
- Demolition costs
- Maintenance costs
- Discounting rate

To structure their expectations, participants were asked three questions: what are the requirements of the ontology? What functionalities should the WLC platform have? And, which analysis should it support? The first question was designed to validate the objectives of the ontology, as it aligns with the requirements of the NeON method from which its construction was derived. This method use the concept of competency questions to express the requirements of the ontology (Suárez-Figueroa, Gómez-Pérez, Motta, & Gangemi, 2012b). Furthermore, it also allows to understand the questions professionals ask about WLC. The group established the following competency questions:

- What is the WLC of the project?
- What are the costs components of the WLC on a given project?
- What is the WLC cash flow of the project?
- What are the financial impacts of the elements and processes on the WLC on a given project?

- What are the expected costs at a specific time?
- What is the life span of the proposed element?

The second question aimed to understand the needs of the practitioner from such an artifact. From the answers of the participants, technical needs that should be integrated in the artifact and decisions they need to be able to make from their interpretation of the results were identified. The group identified the expected functionalities presented in Tableau 4.2.

Tableau 4.2 Expected functionalities from the focus group

	Technical capabilities needed	Decision making actions
What functionalities should have a WLC analysis platform?	<ul style="list-style-type: none"> - Establish the frequency of maintenance/repair - Define maintenance costs accurately - Define a discount rate - Assess the monetary impacts of repairs on used workers - Manual inputs related to model data - Assists in product selection with their useful life - What is the lifespan of the proposed solution? - Sensitivity analysis 	<ul style="list-style-type: none"> - Give the customer any information of the need for use - Choosing the most advantageous investment option - Assess the optimum service life of the structure - Prevention of systemic maintenance

Considering the interface itself, participants expect that it should inform them of the inputs and data required for the analysis, to be user-friendly, with automatic calculations and that all information should be verifiable. The outcomes of this evaluation informed the functional

and data integration requirements implemented in the artifact's design and development phases.

4.5.3 Artifact construction

This section describes the different features of the semantic platform. This stage corresponds to Step 6 – Artifact Construction of the Design Science Research process, where the conceptual design was instantiated into a functional semantic platform. All examples in this section are based on a simulation created for demonstration purposes. A real case study is presented in the following section.

At the heart of the system, GraphDB hosts the WLCONT0 ontology. GraphDB is an RDF database allowing to store, query, and manage semantic data according to semantic web standards. GraphDB hosts the WLCONT0 ontology and manages all RDF triples representing project elements, costs, and temporal data. It supports automated inference for class hierarchies and semantic alignment, while enabling cost aggregation through SPARQL queries. For this study, the WLCONT0 was mapped with the IfcOWL ontology to ensure the artifact is functional with IFC models. The class `ifcOWL:IfcElement` was declared equivalent to `wlcont0:Element`, which itself is defined as a subclass of `wlcont0:Asset`. Hence, all elements of IFC models are considered subclasses of the `wlcont0:Asset`, inheriting all the core WLCONT0 properties. Figure 4.3 shows that all elements, represented by IFC GUID (i.e.: “3z2oiu2_P4fAGxpU3kPVIf”) are subclass of the `wlcont0:Asset` class.

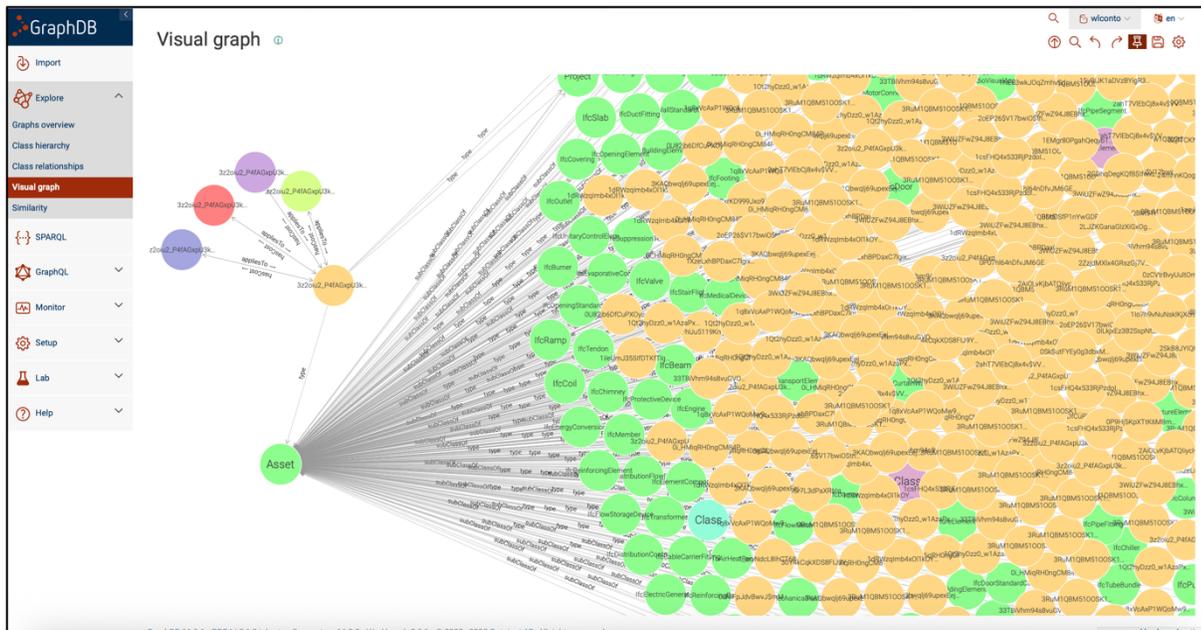


Figure 4.3 Asset Class linked to the IFC model elements

Figure 4.4, present what is characterizing an element instance. As it can be seen, each element is part of both ontologies in the `wlonto:Element` and `ifc:IfcElement`. Each element from the model is now linked with properties from the core ontology by `wlonto:hasDuration`, setting its life span, `wlonto:hasDenomination`, storing the element name from the model, `wlonto:hasUnifomatCode` and `wlonto:hasUnifomatDescription`, storing the element classification from the model, `wlonto:globalID`, storing the IFC GUID from the model, and `wlonto:hasIFCMaterial`, storing the material type from the model.

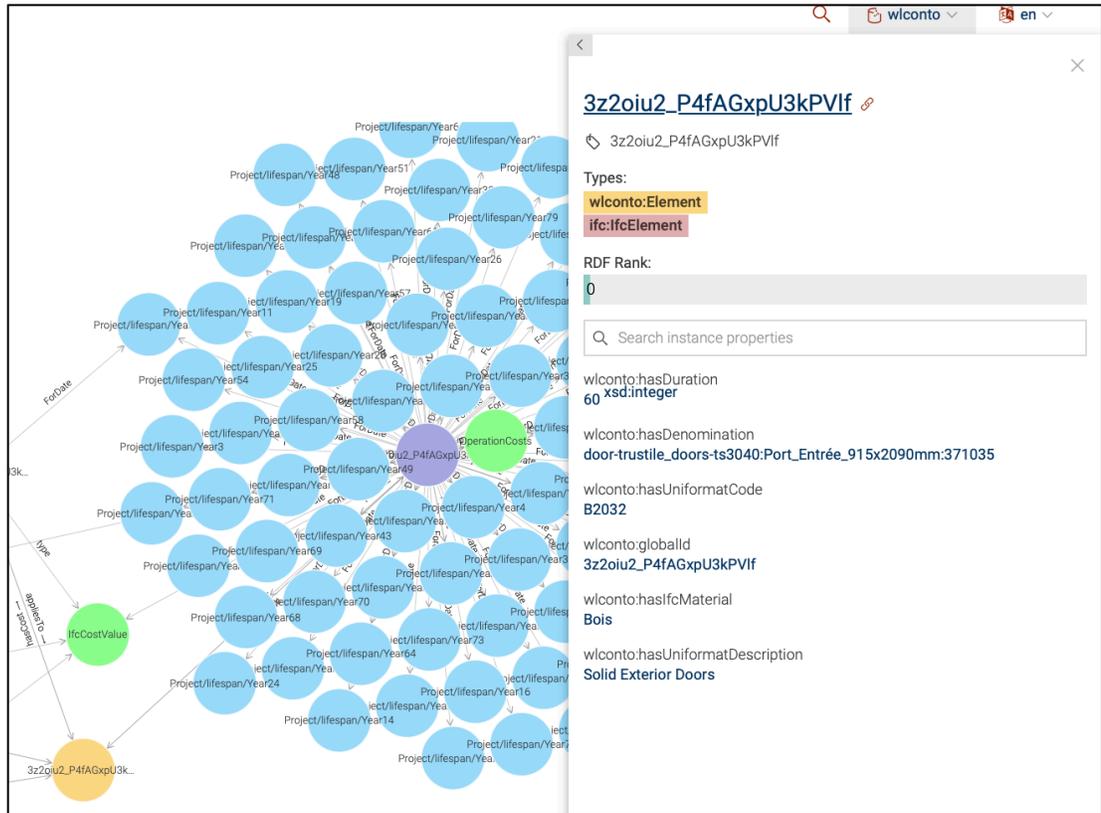


Figure 4.4 Elements details

Considering cost integration, the data property `wlcont:hasCostValue` attributes the costs to the corresponding elements. An example is shown in Figure 4.5.

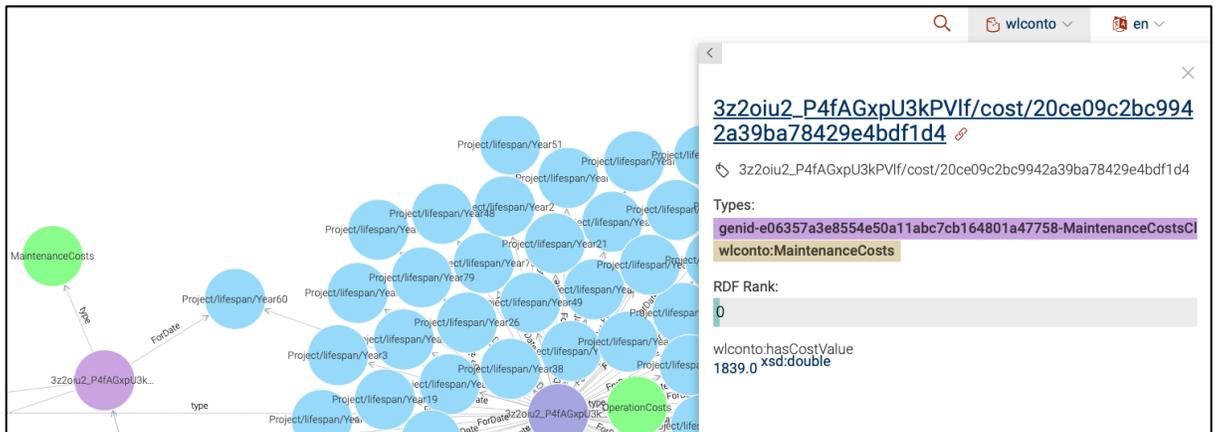


Figure 4.5 Example of cost attribution via the `wlcont:hasCostValue` property

Each element has four types of costs, corresponding to the phases of a project: Construction Costs, Operation Costs, Maintenance Costs and End of life Costs. Each category of cost also has its own class in the WLCONTO. The Figure 4.6 presents the cost structure of a selected element. The element in yellow, is linked to four instances of costs with the object property `wlcont:hasCost`, which themselves are linked to a data property `wlcont:hasCostValue` to get a value. Costs instances are also inversely linked to the element instance with the inverse object property class `wlcont:AppliesTo`, to ensure consistency. Each cost instance is also linked to the `wlcont:Costs` class and its IFC equivalent `ifc:IfcCostValue`, and its corresponding cost category class, all represented in green in the figure. Finally, the time to which the cost appears characterized by the instances of the class `wlcont:Time`, represented in the blue, is linked to the cost instance with the `wlcont:ForDate` object property. This structure ensure that each element has all its life cycle costs modelled at the right time during the period of analysis.

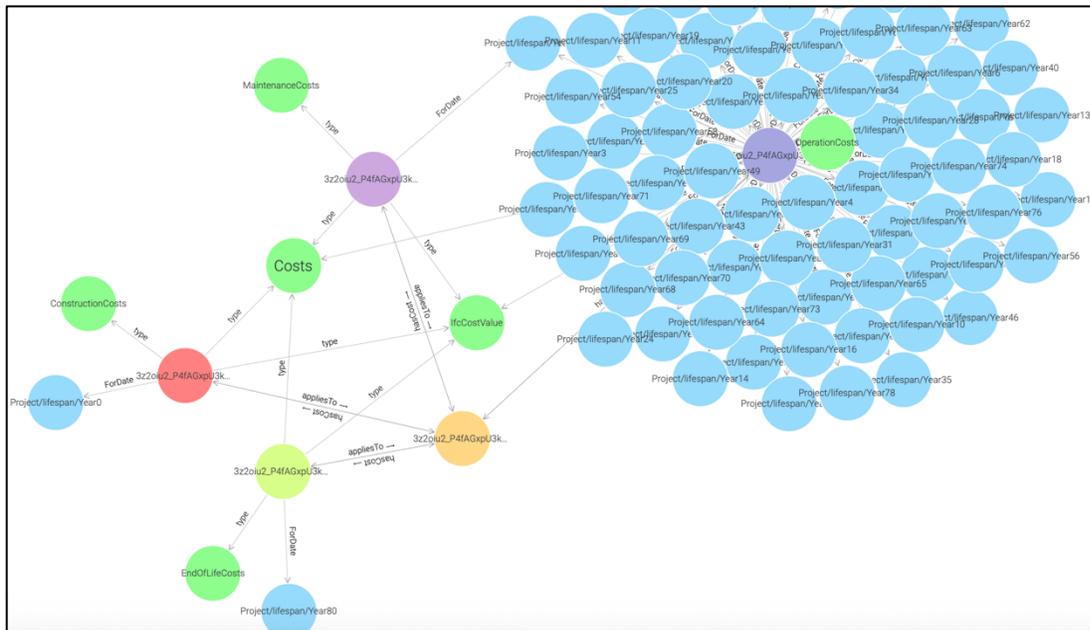


Figure 4.6 WLCONTO costs structure

Considering the need of the focus group to know the financial impacts on stakeholders, the initial core ontology was extended to integrate projects actors and relations to their

financials' responsibilities. It was also facilitated by using the IfcOWL ontology, proposing classes representing persons, organizations, and their roles within building projects. In this approach, a new class `wlconto:Stakeholder` was introduced as a subclass of the IFCOWL class `IfcPersonAndOrganization`. Furthermore, the ontology defines the object properties `wlconto:responsibleFor` to explicitly link stakeholders to the costs for which they are responsible. These concepts are linked to the project's cost structure and lifecycle phases, enabling advanced queries and analyses regarding the distribution and attribution of costs among stakeholders. The alignment with IFCOWL ensures interoperability with BIM data and facilitates the mapping of project actors and their roles from IFC models to the semantic layer (Figure 4.7).

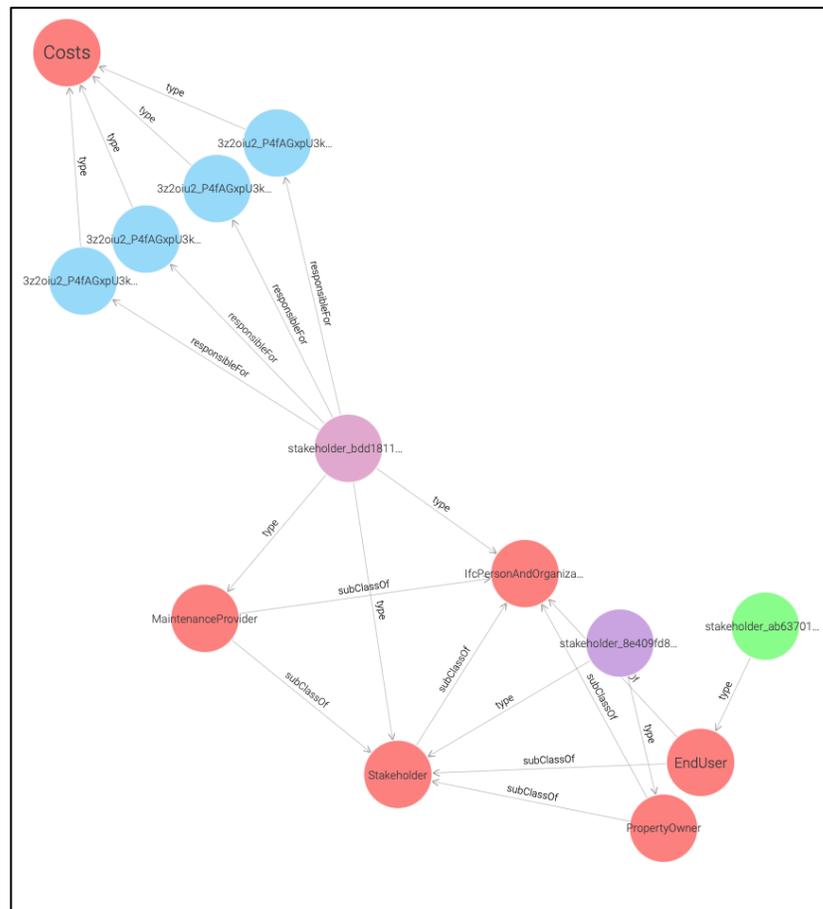


Figure 4.7 Stakeholders modeling in WLCONTO

4.5.4 Evaluation n°3: demonstration of the constructed prototype

4.5.4.1 Artifact architecture

To evaluate the constructed artifact, a demonstration was performed to showcase how the proposed semantic platform operates and how its components interact within the KGDB environment. The proposed platform articulates itself around this KGDB, allowing the displaying and interpretation of the WLC analysis. The full platform architecture is presented in Figure 4.8. The user interacts with a first layer, being the frontend revealing the user interface. This layer has been developed in HTML, CSS and JavaScript with Chart.js enabling users to navigate between different tabs. The backend, built with Flask, manages the processes through several specialized modules: the IFC parser, which extracts and transforms data from IFC models using the ifcopenshell library; the SPARQL client, which achieves all interactions with the GraphDB knowledge base via SPARQL queries; the WLC calculator, which performs time discounting and WLC calculation; and the File manager, which imports and produces Excel reports and enriched IFC files. The final layer is the core Ontology previously presented. All computations are triggered through the Python backend, but data remain continuously synchronized within the RDF store through automated SPARQL updates.

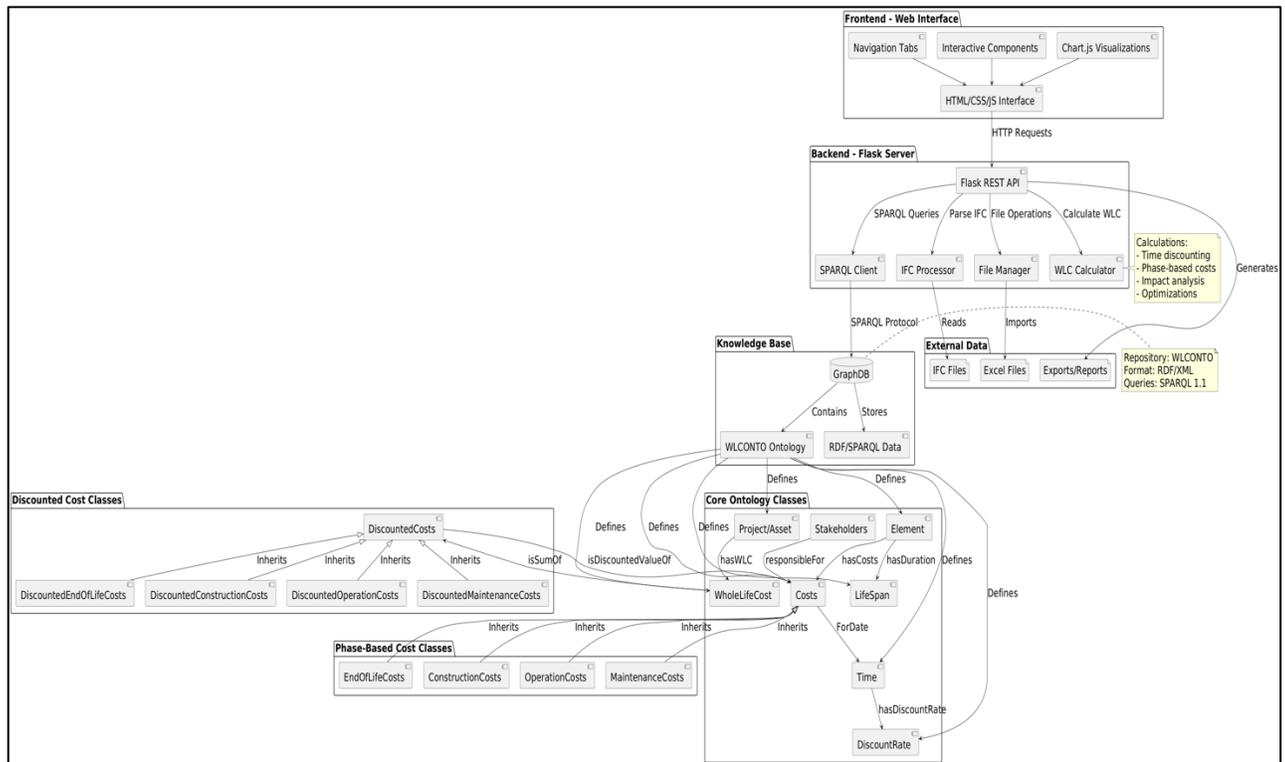


Figure 4.8 Semantic platform architecture

4.5.4.2 Operational workflow

As presented in the Figure 4.9, the operational workflow starts with the user inputting an IFC model containing project information and its elements, into the dedicated tab of the platform. At this stage, the model is parsed and semantically aligned with the corresponding IfcOWL classes before integration into GraphDB. Each element must include its ifcGUID to ensure traceability throughout the analysis process. To facilitate verification and maintain consistency with professional practices, elements are expected to include an appropriate classification. Finally, model consistency is verified to identify the information required for the WLC analysis and to complete missing data where necessary.

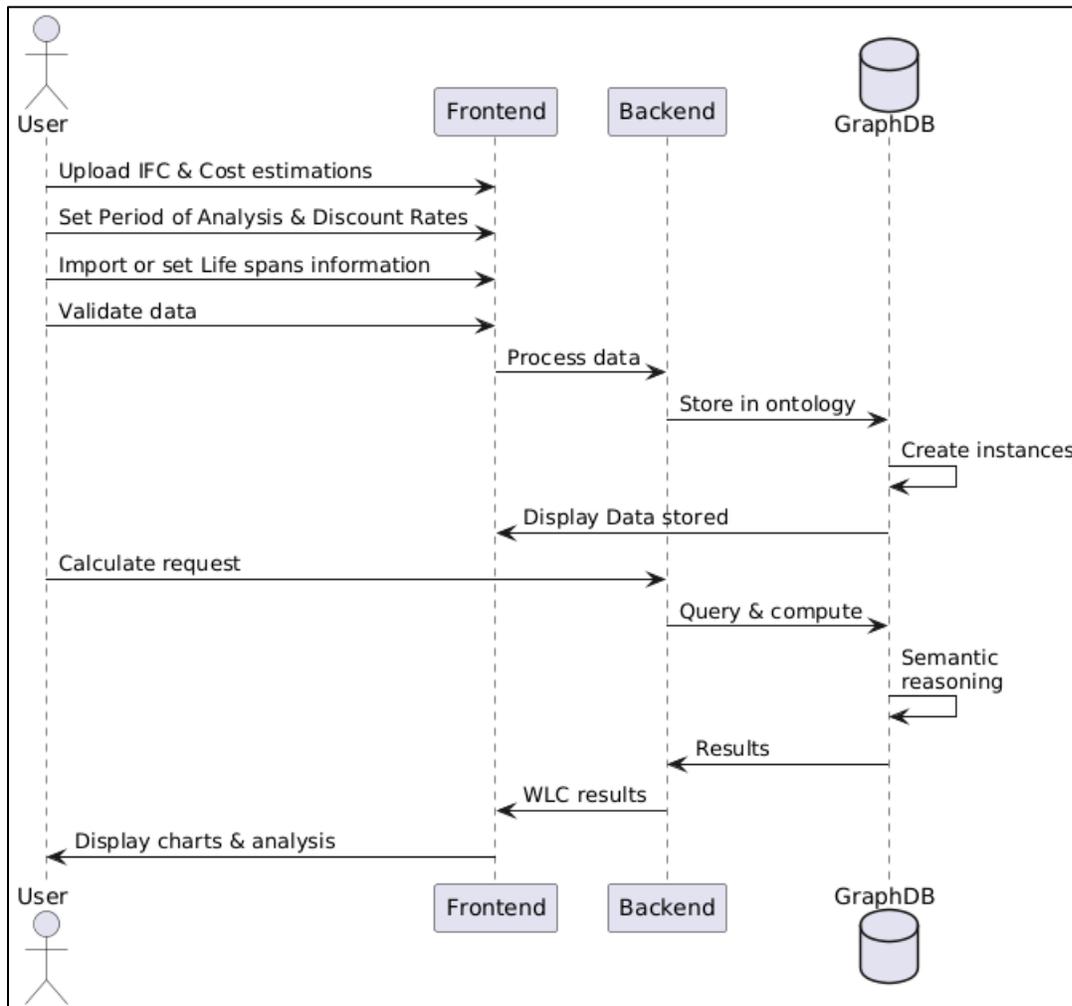


Figure 4.9 User process for WLC analysis through the proposed artifact

The next inputs are different estimations corresponding to each life cycle phases, if the IFC model does not provide this cost information. The estimations spreadsheets are ideally aligned with the uploaded IFC model, thanks to an IfcGUID for each element, no matter the classification used. Otherwise, an additional mapping is necessary to ensure that each cost is aligned with its corresponding element. The analyst defines the WLC parameters directly within the platform. First, he must set the period of analysis of the project. This action will automatically create an even number of year instances into the class “Year” within the KGDB, to ensure the possibility to attribute a year to a cost (i.e. A period of 50 years will create 50 instances of Year into the KDGB, as Year 1, Year 2..., Year 50). If available, a lifespan database can be uploaded to automatically assign durations to elements based on

their materials. Missing data can also be completed manually by assigning materials or lifespans to the concerned elements. To finish the input phase, the user will also have to manually set the discount rate of the project, which can be even for the whole period of analysis or personalized for each year. Before performing the WLC calculation, the platform displays all elements for validation and allows direct data modification, which automatically updates the KGDB (Figure 4.10).

<input type="checkbox"/>	GLOBALID	UNIFORMAT	DESCRIPTION	MATÉRIAU	CONSTRUCTIO N (\$)	OPÉRATION (\$)	MAINTENANCE (\$)	FIN DE VIE (\$)	DURÉE (ANNÉES)
<input type="checkbox"/>	2C2_zibRrBqP8UOfTsZnN	A1012	Column Foundations ...	Fondation béton	1371,0	10,0	1371,0	1371,0	60
<input type="checkbox"/>	0dGOFPO4P0PAP8cNXV...	A1012	Column Foundations ...	Fondation béton	310,0	10,0	310,0	310,0	60
<input type="checkbox"/>	3\$mUw1Q3b2dhsiUaFiX...	A1012	Column Foundations ...	Fondation béton	450,0	10,0	450,0	450,0	60
<input type="checkbox"/>	OK2YFhUu5119KmWDh...	A1012	Column Foundations ...	Fondation béton	744,0	10,0	744,0	744,0	60

Figure 4.10 Elements displaying

The KGDB facilitates the WLC analysis by serving as the central repository where new instances and updated cost values are written automatically through SPARQL Update commands triggered by the backend. SPARQL queries extract nominal cost data by IFC item, while the backend organizes them over the project timeline and updates GraphDB with the corresponding annualized instances. This approach eliminates manual calculations and makes data management easier. To get the final calculation the user can simply push the corresponding button, and the platform displays the total WLC, and the cash flows of nominal and discounted costs of the project through its life cycle (Figure 4.11).



Figure 4.11 WLC results

To complete the loop and provide feedback to the design team, the platform also provides the possibility to enrich IFC files with WLC data (Figure 4.12). This functionality is possible thanks to the ifcGUID that link elements with data.

Window-Awning-Kolbe-Ultra_Series_Crank-Out_Awning-1Wx2H:Fenêk..	
▼ WLC_CostData	
Construction_Cost	261
Operation_Cost	800
Operation_Cost_Annual	10
Maintenance_Cost	522
Maintenance_Cost_Unit	261
Number_of_Replacements	2
End_of_Life_Cost	261
Element_Lifespan	30

Figure 4.12 IFC model enrichment with WLC data

To go further, and help the user to interpret the WLC, functionalities based on SPARQL queries was implemented. The SPARQL queries allow leveraging the KGDB to reveal

insights about the project whole life cost. First, a cost impact analysis identifies the costliest elements in the project lifecycle (Figure 4.13). Secondly, a frequent replacement analysis uses the lifetimes defined in the ontology to calculate the number of replacements needed over the life of the project, revealing the elements that generate recurring costs and require attention in the maintenance strategy (Figure 4.14). Third, a high maintenance analysis identifies the elements that require high maintenance budgets for the project (Figure 4.15). Next, the phased cost analysis breaks down the budget allocation across the four lifecycle phases, revealing which phase dominates financially and requires the most strategic attention (Figure 4.16). Lastly, the platform gives the possibility to attribute cost responsibilities, analysing costs implications for each registered stakeholder (Figure 4.17).

Élément le plus coûteux: Pile Foundations (\$5,998.00)

Impact des Coûts 50 éléments [Exporter Excel](#)

GUID	DESCRIPTION	MATÉRIAU	CONSTRUCTION	OPÉRATION	MAINTENANCE	FIN DE VIE	TOTAL
3RuM1QBMS100SK1X2RGUGc	Pile Foundations	Aluminium	\$2,000.00	\$10.00	\$1,994.00	\$1,994.00	\$5,998.00
0P07h164ndfvJM6GEVqUc5	-	Wood	\$1,989.00	\$10.00	\$1,989.00	\$1,989.00	\$5,977.00
3KAQbwqLj69upexEej3bwg	Grade Beams	Bois	\$1,977.00	\$10.00	\$1,977.00	\$1,977.00	\$5,941.00
01_HMiqRH0ngCM84Pnxn8J	Fixed Partitions	Plâtre	\$1,975.00	\$10.00	\$1,972.00	\$1,975.00	\$5,932.00
1XzeLxhBPDaxC7lgixNyFC	Exterior Louvers, Screens, and Fencing	Aluminium	\$1,974.00	\$10.00	\$1,974.00	\$1,974.00	\$5,932.00
3RuM1QBMS100SK1X2RJXEY	Exterior Louvers, Screens, and Fencing	Aluminium	\$1,963.00	\$10.00	\$1,963.00	\$1,963.00	\$5,899.00
1dRwzqImb4x0L1kOYfjJWb	Exterior Louvers, Screens, and Fencing	Aluminium	\$1,956.00	\$10.00	\$1,956.00	\$1,956.00	\$5,878.00
3RuM1QBMS100SK1X2RGUa\$	Exterior Louvers, Screens, and Fencing	Aluminium	\$1,949.00	\$10.00	\$1,949.00	\$1,949.00	\$5,857.00
3RuM1QBMS100SK1X2RJXEU	Exterior Louvers, Screens, and Fencing	Aluminium	\$1,944.00	\$10.00	\$1,944.00	\$1,944.00	\$5,842.00
3RuM1QBMS100SK1X2RGUnG	Exterior Louvers, Screens, and Fencing	Aluminium	\$1,922.00	\$10.00	\$1,922.00	\$1,922.00	\$5,776.00
30Y4kCqkXDS8FIJ9YwxE10	Pile Foundations	Aluminium	\$1,916.00	\$10.00	\$1,916.00	\$1,916.00	\$5,758.00
33TB1Vhm94s8vuGV0JEn60	Exterior Wall Construction	Brique	\$1,915.00	\$10.00	\$1,915.00	\$1,915.00	\$5,755.00
3RuM1QBMS100SK1X2RGUXC	Pile Foundations	Aluminium	\$1,902.00	\$10.00	\$1,902.00	\$1,902.00	\$5,716.00

Figure 4.13 Cost impact analysis

Résumé de l'Analyse
Description: Éléments nécessitant des remplacements fréquents sur 80 ans

Remplacements Fréquents 4 éléments [Exporter Excel](#)

GUID	DESCRIPTION	MATÉRIAU	CONSTRUCTION	OPÉRATION	MAINTENANCE	FIN DE VIE	TOTAL
3z2o1u2_P4fAGxpU3kPw1JM	Windows	Double vitrage	\$0.00	\$0.00	\$411.00	\$0.00	\$0.00
3z2o1u2_P4fAGxpU3kPwPpK	Windows	Double vitrage	\$0.00	\$0.00	\$507.00	\$0.00	\$0.00
3z2o1u2_P4fAGxpU3kPZL3	Windows	Double vitrage	\$0.00	\$0.00	\$837.00	\$0.00	\$0.00
3z2o1u2_P4fAGxpU3kPZuF	Windows	Double vitrage	\$0.00	\$0.00	\$1,030.00	\$0.00	\$0.00

Figure 4.14 Frequent replacements analysis

Maintenance Élevée 28 éléments [Exporter Excel](#)

GUID	DESCRIPTION	MATÉRIAU	CONSTRUCTION	OPÉRATION	MAINTENANCE	FIN DE VIE	TOTAL
3RuM10BMS100SK1X2RGUGC	Pile Foundations	Aluminium	\$0.00	\$0.00	\$1,994.00	\$0.00	\$0.00
0P07h1L64ndfvJMG6EVqUcS	-	Wood	\$0.00	\$0.00	\$1,989.00	\$0.00	\$0.00
3KA0bwq1j69upexEej3bwq	Grade Beams	Bois	\$0.00	\$0.00	\$1,977.00	\$0.00	\$0.00
1XzeLxhBP0axC7lg1xNyFC	Exterior Louvers, Screens, and Fencing	Aluminium	\$0.00	\$0.00	\$1,974.00	\$0.00	\$0.00
0i_HM1qRH0ngCMB4Pnxn8J	Fixed Partitions	Plâtre	\$0.00	\$0.00	\$1,972.00	\$0.00	\$0.00
3RuM10BMS100SK1X2RJXEY	Exterior Louvers, Screens, and Fencing	Aluminium	\$0.00	\$0.00	\$1,963.00	\$0.00	\$0.00
3W1UZfwZ94J8EBhxXZAgug	Fixed Partitions	Plâtre	\$0.00	\$0.00	\$1,957.00	\$0.00	\$0.00
1dRWzq1mb4x0L1kOYf1JWb	Exterior Louvers, Screens, and Fencing	Aluminium	\$0.00	\$0.00	\$1,956.00	\$0.00	\$0.00
3RuM10BMS100SK1X2RGUas	Exterior Louvers, Screens, and Fencing	Aluminium	\$0.00	\$0.00	\$1,949.00	\$0.00	\$0.00
3RuM10BMS100SK1X2RJXEU	Exterior Louvers, Screens, and Fencing	Aluminium	\$0.00	\$0.00	\$1,944.00	\$0.00	\$0.00
1Qt2hy0zz8_w1AzaPx0_HH	Interior Doors	Bois	\$0.00	\$0.00	\$1,940.00	\$0.00	\$0.00
1Qt2hy0zz8_w1AzaPx0_7o	Interior Doors	Bois	\$0.00	\$0.00	\$1,929.00	\$0.00	\$0.00
3W1UZfwZ94J8EBhxXZAg_6	Exterior Wall Construction	Brique	\$0.00	\$0.00	\$1,924.00	\$0.00	\$0.00
3RuM10BMS100SK1X2RGUng	Exterior Louvers, Screens, and Fencing	Aluminium	\$0.00	\$0.00	\$1,922.00	\$0.00	\$0.00

Figure 4.15 Maintenance Analysis

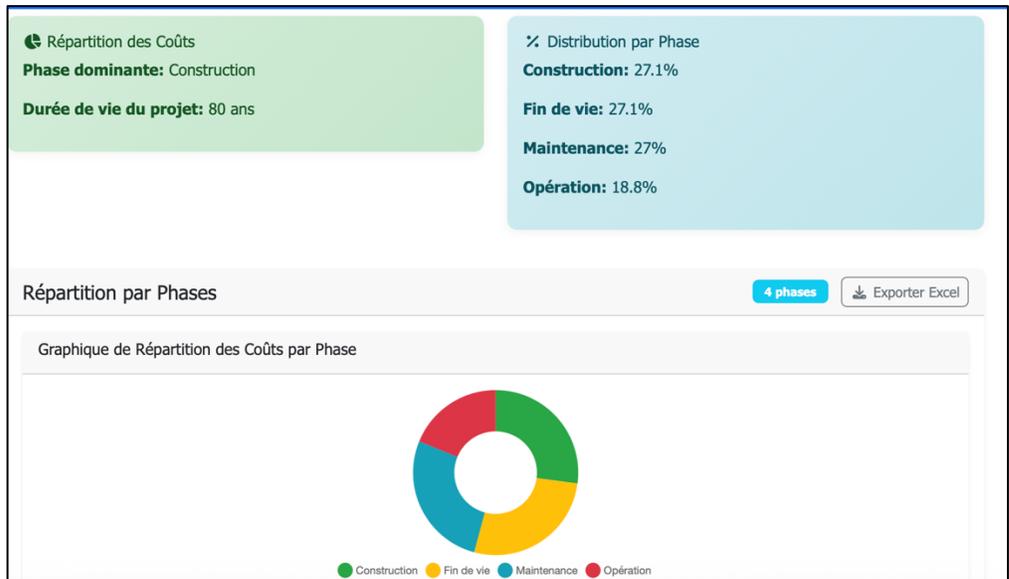


Figure 4.16 Phased costs analysis

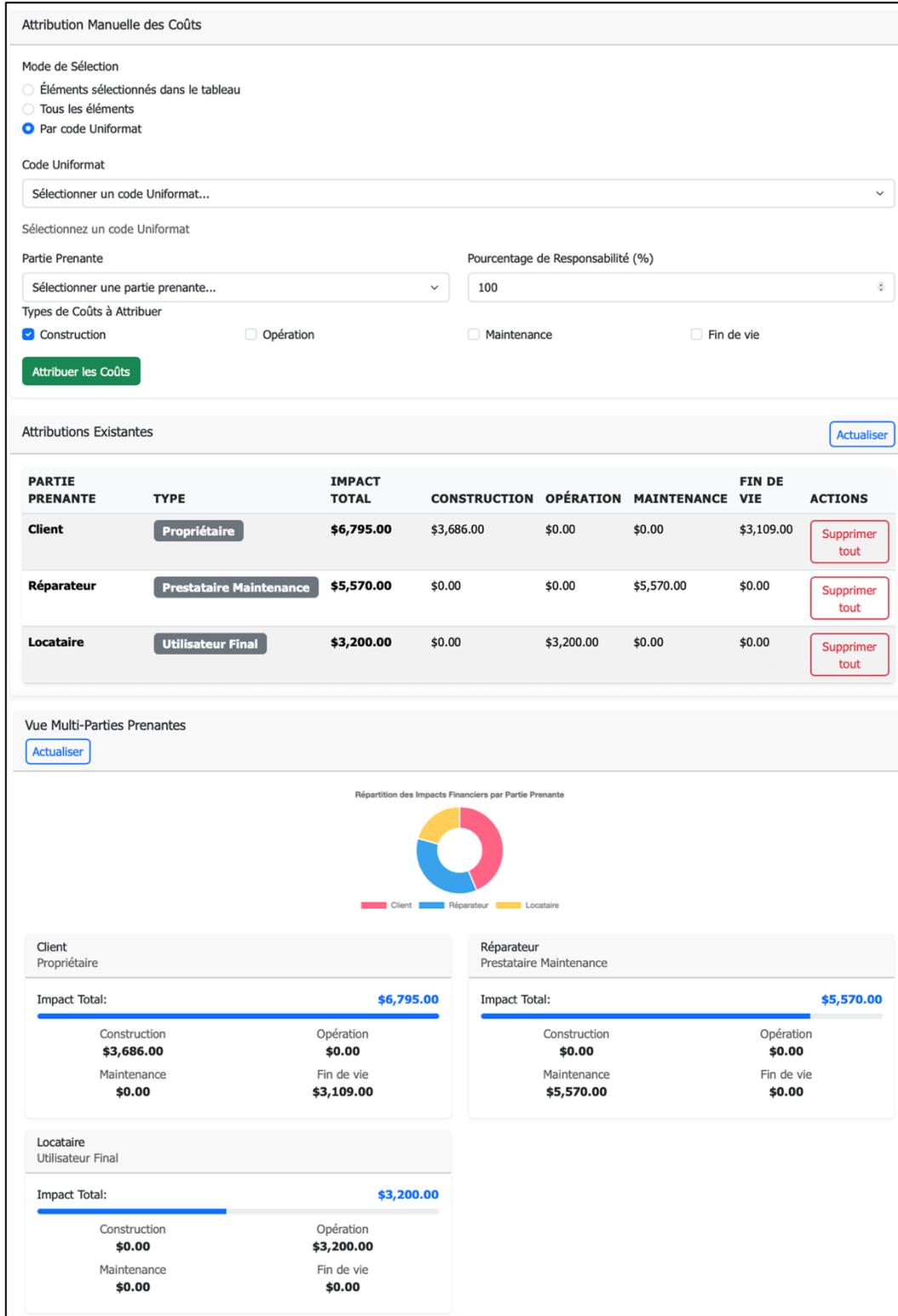


Figure 4.17 Cost responsibilities analysis

Finally, the platform also supports comparative scenario analysis by enabling the structured evaluation of design alternatives over the project life cycle (Figure 4.18). By adjusting one project parameter at a time, users can observe the corresponding variations in lifecycle costs. The platform operationalizes this through a dedicated feature that allows users to download the enriched Knowledge Graph, including the calculated WLC results, as a .ttl file. These scenario-specific graphs can later be reuploaded and queried side by side, offering a traceable and semantically consistent method to compare options across time, cost categories, and stakeholder responsibilities. This feature enhances the decision-making process by enabling data-driven exploration of trade-offs between technical alternatives, while maintaining alignment with the original project structure and semantics.

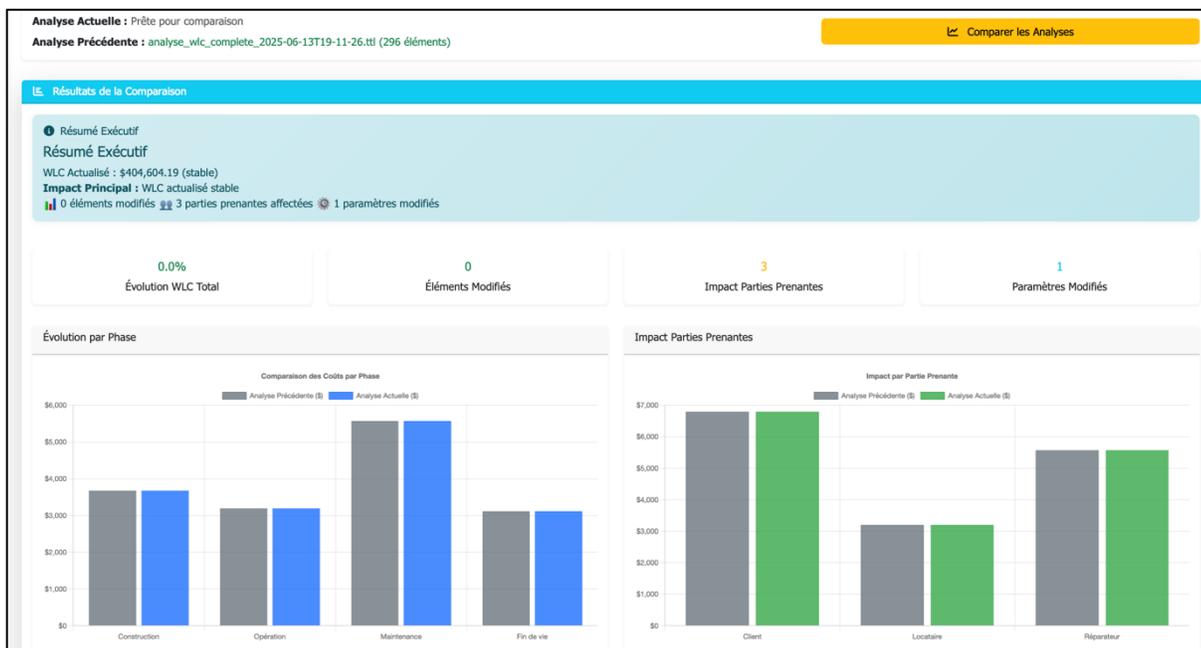


Figure 4.18 Comparative analysis of different scenarios

This stage validated the artifact's capability to operationalise dynamic WLC analysis through a fully integrated semantic workflow, combining automated data processing, reasoning, and decision-support functionalities.

4.5.5 Evaluation 4: use and Artificial-Ex Post evaluation

To achieve the prototype evaluation, a real-world scenario was deployed. This case was used to assess the platform's capacity to handle real project data, execute WLC calculations, and support comparative analysis between design alternatives. The study was conducted in collaboration with a public owner organization in the province of Quebec, Canada. The project consisted in the construction of a high-school located in Quebec City. For this analysis, the scope covers the building envelop and its impact on the HVAC equipment. The envelope is comprised of 3,625 m² of high-performance curtain walls and 5,105 m² of opaque walls (152 mm steel studs, bituminous vapour barrier, 200 mm rock wool insulation; $R \approx 4,6 \text{ m}^2 \cdot \text{K/W}$). The flat roof with white elastomeric coating ($R \approx 7 \text{ m}^2 \cdot \text{K/W}$) covers 8,055 m². The HVAC system consists of two 250 kW electric boilers, 150 T water-to-water heat pumps with a cooling capacity of 1,055 kW, and six AWUs/UV (20,000–35,000 CFM) supplying 80,188 L/s of fresh air. The model uses a constant discount rate of about 3%, the period of analysis is settled for 50 years, considers service lives of 50 years for the heavy envelope, 30–35 years for power plants (boilers, chillers, AWUs/UV) and 20 years for auxiliaries.

Two scenarios were considered for comparison: The as-built scenario for reference (Tableau 4.3), and a reduction of 700 m² of curtain wall area, replaced by opaque wall as already designed in the project (Tableau 4.4). The capital costs come from the bill of quantities that were prepared for the project. Operating costs include calculated consumption (utilization factor 2,000 h/year heating, 600 h/year cooling) and the institutional rate of Hydro-Québec, the region's main supplier. Maintenance costs, including preventive maintenance, end-of-life equipment repair and demolition costs, are based on RSMMeans databases.

The analysis also aimed to verify whether the KGDB correctly attributed costs by phase and stakeholder responsibility, as defined in the WLCONTTO structure. The public owner shall assume responsibility for construction and demolition costs, while the occupant, represented by the school board, shall be accountable for operation, consumption, and maintenance costs.

Tableau 4.3 Reference scenario for comparison

UNIFORMAT II description	Investment costs \$	Operation costs \$	Maintenance costs \$	End of Life Costs \$
Curtain Walls (3 625 m ²)	4 227 864	43 500	10 875	108 750
Exterior Wall (5 105 m ²)	4 149 907	5 800	11 800	145 000
HVAC	4 045 709	45 000	4 000	300 000
Cooling	743 700	36 000	2 500	100 000
Autonomous units	1 738 000	13 000	3 000	190 000
Heat production	323 600	62 500	2 000	48 500

Tableau 4.4 Alternative scenario for comparison

UNIFORMAT II description	Investment costs \$	Operation costs \$	Maintenance costs \$	End of Life Costs \$
Curtain Walls (2 925 m ²)	3 411 252	35 100	8 775	87 750
Exterior Wall (5 805 m ²)	4 718 943	6 600	11 800	145 000
HVAC	4 045 709	45 000	4 000	300 000
Cooling	743 700	34 500	2 500	100 000
Autonomous units	1 738 000	13 000	3 000	190 000
Heat production	323 600	55 500	2 000	48 500

As shown in Figure 4.19 and Figure 4.20, the reference scenario resulted in a higher NPV of 27.91 M\$, compared with 26.56 M\$ for the alternative. Phase-based analysis revealed that the reference option incurred greater costs across all lifecycle stages. The stakeholder-based visualization effectively demonstrated the capacity of the platform to distinguish cost

responsibilities across project actors, validating its ability to represent cost ownership structures.

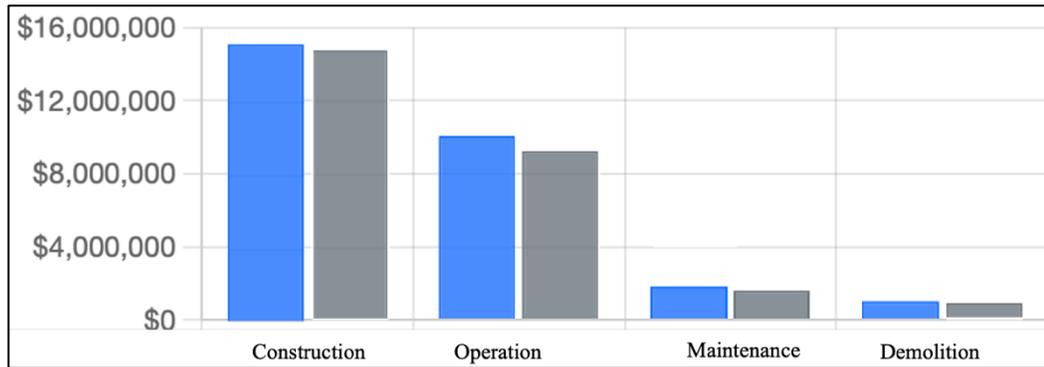


Figure 4.19 Cost repartition by phase, blue= reference scenario, grey= alternative scenario

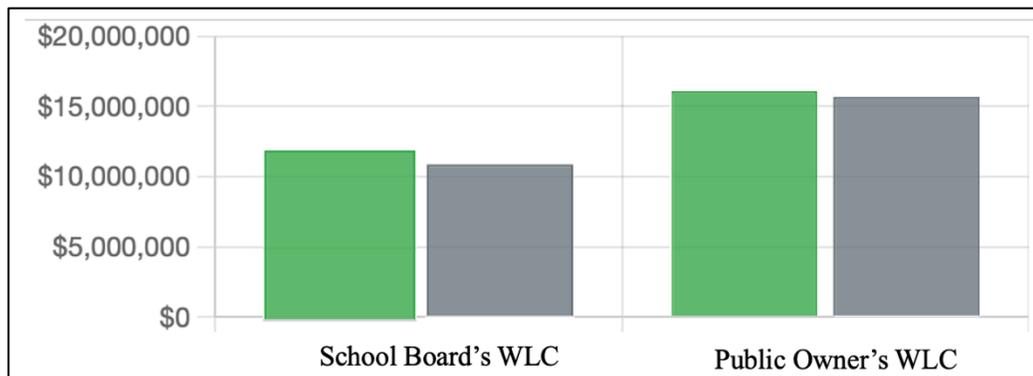


Figure 4.20 Cost repartition by stakeholders. On the left, School Board's WLC, on the right, Public Owner's WLC. green= reference scenario, grey= alternative scenario

4.6 Discussion

The present research aimed to demonstrate how a KGDB can be used to support dynamic WLC computation, scenario comparison, and collaborative analysis. Building on a core ontology aligned with ISO 15686-5, the proposed artifact demonstrates how a KGDB can serve as an appropriate system to support dynamic WLC computation and interpretation. This ontology provides a unified semantic layer that enables automated reasoning and consistent WLC analysis. This approach goes beyond conceptual modelling to demonstrate

the practical use of semantic technologies for WLC simulation and decision support during early design stages, where financial evaluations have the greatest strategic impact.

The adoption of a KGDB architecture was central to the platform's ability to operationalise WLC. Unlike most existing BIM-based tools that rely on static exports or disconnected spreadsheets, the KGDB enables dynamic reasoning through continuous data integration. By leveraging an RDF-based infrastructure, the platform ensures that modifications in BIM models or estimation files are automatically reflected within the graph, preserving consistency. This architecture leverages data virtualization to enable the querying and interpretation of heterogeneous sources without physical duplication. In the context of WLC, this design choice reduces data redundancy, strengthens interoperability and ensures that cost information remains synchronised with evolving design and estimation data. Compared to property graph implementations, the RDF-based approach demonstrates higher expressivity and alignment with established Semantic Web standards. This ensures interoperability with existing ontologies, such as IfcOWL, while maintaining the logical reasoning necessary for inference. The results therefore highlight the KGDB not only as a data management solution but as a computational medium capable of supporting design-stage analysis and decision-making. The novelty of the proposed approach thus lies on its integration into a single semantic workflow supporting continuous WLC analysis.

When compared with prior works, the present study demonstrates a distinct evolution in both purpose and implementation. El-Diraby (2006) laid the conceptual foundations for LCC through an ontological representation of construction processes and their financial relationships. His environment relied on a service-oriented architecture in which lifecycle cost data were exchanged between independent modules rather than integrated into a single knowledge structure. This configuration supported collaborative management of cost information but remained descriptive and disconnected from operational computation. More recently, Shaw (2025) advanced the field by introducing the LCAIM ontology, instantiated within a property-graph environment. Their solution applied graph-based principles to manage asset information for policy reporting, combining Cypher queries with external

Python functions to perform lifecycle cost calculations before reinjecting the results into the graph. In contrast, the present study positions WLC computation itself as a core function of the semantic infrastructure, explicitly supporting iterative scenario-based design decisions.

Moreover, the present study adopts an RDF-based KGDB architecture in which the ontology, reasoning, and computation modules operate within a unified semantic framework. GraphDB acts as both storage and aggregation layer through SPARQL queries that compute cost totals and maintain semantic alignment between heterogeneous sources. The Python backend orchestrates the WLC analysis by retrieving aggregated data, executing discounting computations, and automatically writing the updated results back into the KGDB through SPARQL UPDATE. This workflow ensures a continuous and synchronized loop between data extraction, computation, and reinjection, eliminating the discontinuities typically observed in previous implementations. Furthermore, whereas Shaw's approach focuses primarily on the asset-management phase, the proposed framework focuses on the design-stage decision process, reflecting the estimator's need to simulate, compare, and iterate dynamically on cost alternatives. By embedding temporal and financial reasoning directly into the ontology, the platform operationalises WLC as an analytical and collaborative process rather than a retrospective reporting mechanism. Such capabilities are particularly relevant in early design phases, where cost engineers must support negotiations and trade-off analyses among multiple stakeholders.

Beyond its technical contribution, the proposed platform also redefines the analytical and collaborative roles of WLC in construction projects. By embedding financial, temporal, and stakeholder dimensions within a unified semantic framework, the KGDB enables both machine reasoning and human interpretation to operate on the same data layer. This dual capacity turns WLC into a dynamic decision-support system rather than a static evaluation method. Cost engineers can query, visualise, and compare lifecycle outcomes in real time, while project actors can trace cost responsibilities and understand their long-term implications. The integration of stakeholders and their financial obligations within the ontology introduces a new layer of accountability and transparency, aligning with the

principles of collaborative procurement. This semantic traceability also fosters knowledge continuity between project stages, supporting iterative learning and reuse of structured cost information.

4.7 Conclusion and future works

The research presented in this paper aimed to operationalise the WLC analysis through a dynamic semantic platform. It addressed the persistent challenge of linking design, cost, and lifecycle information in a coherent and computable form. The proposed platform demonstrates how a KGDB can support this integration by connecting reasoning, computation, and visualisation within a single semantic environment. Building upon a WLC ontology structured according to ISO 15686-5, the system virtualises heterogeneous data sources, such as BIM models and cost estimations, and transforms them into a machine-interpretable structure that supports automated calculations and temporal reasoning.

The work contributes both methodologically and technically. Methodologically, it applies semantic web principles to the specific problem of cost lifecycle analysis, bridging ontology engineering with design-stage economic reasoning. Technically, the platform embeds WLC logic within the knowledge model itself, allowing the KGDB to act not merely as a data repository but as a computational infrastructure. This architecture ensures continuity between data, reasoning, and results, while maintaining interoperability with BIM environments. The artifact demonstrates that lifecycle computations can be executed directly through the semantic layer, rather than through external scripts or spreadsheets. The platform enables structured WLC analysis across all project phases and supports real-time interpretation of results through SPARQL queries. Users can explore lifecycle costs, stakeholder responsibilities, and scenario variations through an integrated and traceable process.

Compared with traditional BIM-based estimation workflows, the proposed approach reduces fragmentation by ensuring that each piece of information remains semantically linked and

dynamically updated. This transition from static file-based management to graph-based computation redefines how cost analysis can be embedded in digital project environments. Beyond technical implementation, the framework also contributes to broader reflections on transparency and collaboration in cost management. The artifact enables accountability tracking across the lifecycle. This supports the adoption of collaborative governance in project delivery. Furthermore, by formalising WLC as a queryable and extensible knowledge base, the study aligns lifecycle economics with the ongoing digitalisation of the construction sector, where interoperability and shared data environments are central.

Despite its promising results, the present work still faces several limitations that highlight opportunities for future research. The platform's performance depends largely on the efficiency of SPARQL query execution and the optimization of the RDF triple store, which may become a constraint as datasets grow in size and complexity. In other words, system performance depends on query optimisation and database scalability as data volumes increase. The need for strictly formatted input data (e.g., structured spreadsheets and well-defined IFC models) can also limit accessibility for practitioners unfamiliar with semantic technologies. While this requirement ensures data integrity, it places additional responsibility on users for preprocessing and data verification. Moreover, the current platform acts as a semantic infrastructure rather than a fully autonomous system, relying on the completeness and consistency of external data sources. Enhancing its capacity to extract and structure unformatted information, for instance through Natural Language Processing (NLP), would expand its practical applicability.

Another avenue concerns the integration of predictive and adaptive models. The structured nature of the KG makes it well suited for coupling with Machine Learning algorithms or generative AI models capable of identifying cost patterns, forecasting maintenance events, or simulating design alternatives. Extending the platform toward such hybrid reasoning could enable anticipatory cost management across project stages. Finally, broader validation with real projects and multidisciplinary teams is required to assess its scalability, interoperability, and integration in project practices. In this perspective, the proposed framework constitutes a

foundational step toward the digital transformation of cost engineering, paving the way for integrated and collaborative cost management environments.

These aspects underline the importance of continuous refinement of the ontology and the development of automated routines for data ingestion and validation. Future work will focus on enhancing the scalability and usability of the framework. Priority should be given to extending the ontology to include environmental and social impact dimensions, strengthening its ability to support holistic lifecycle assessments. In parallel, improving the automation of data integration and exploring the coupling between semantic reasoning and predictive analytics would expand the platform's analytical scope.

4.8 References

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CHAPITRE 5

DISCUSSION

5.1 Introduction

Cette section présente une discussion visant à fournir des réflexions sur la méthodologie de recherche et les résultats obtenus afin de définir plus précisément leur impact, tant pour la pratique que la recherche. Aussi, l'originalité de la recherche et ses contributions sont explicitées. Pour finir, la diffusion des résultats est expliquée et des pistes de travaux futurs sont exposées.

5.2 Discussion sur la méthodologie

5.2.1 Application de la méthodologie

Pour mener ce projet de recherche, nous avons choisi de suivre la méthodologie de la Recherche en Science de la Conception, cadrée dans le paradigme pragmatique. Le choix de cette approche a été motivé par la volonté de proposer une solution à un problème pratique. Face à un besoin d'une solution opérationnelle du coût global, notre recherche a centré la méthodologie de conception autour d'une ontologie. Ainsi, il a été possible à la fois d'assurer une contribution théorique, mais aussi pratique par la révision de l'ontologie avec son environnement d'application et domaine de connaissance.

La littérature montre que les études doctorales suivant la méthodologie de la RSC manquent souvent de compréhension et de rigueur dans l'application de la méthodologie (Cater-Steel, Toleman, & Rajaeian, 2019a). Afin d'assurer la compréhension et l'application de la méthodologie, nous reprenons dans le Tableau 5.1 ci-dessous, l'ensemble des étapes définies précédemment afin d'en assurer la bonne application.

Tableau 5.1 Validation d'application des étapes de recherche

Étape 1 : Définition du problème	Le problème a été décrit en première partie de la thèse, émanant de motivations pratiques et théoriques.
Étape 2 : Exploration du problème	Le problème identifié, pour le côté pratique, a été exploré dans un premier temps grâce à la réalisation d'un sondage auprès de professionnels membres de l'AEÉCQ, confirmant ce qui avait été identifié. Une exploration plus profonde a ensuite été réalisée grâce à des entrevues semi-structurées, permettant de recueillir des témoignages des professionnels sur leurs expériences liées à l'approche. Pour le côté théorique, une revue systématique de la littérature, présentée en ANNEXE I, a permis d'explorer les solutions alors en tendances dans le monde de la recherche.
Étape 3 : Exigences de conception de l'artefact	L'analyse des données des entrevues, croisées avec celles du sondage ont permis de définir les enjeux et besoins d'adoption du coût global. Dans le but d'assurer la compréhension de l'environnement d'intégration, une exploration portant sur les sujets du BIM et l'interopérabilité a été réalisée. Ainsi, l'article en ANNEXE II a permis de comprendre les enjeux et nécessités d'utilisation d'une approche BIM favorisant l'utilisation de données ouvertes.
Étape 4 : Conception de l'artefact	La conception de l'artefact a pu être réalisée par l'entremise d'un groupe de réflexion, avec lequel les spécificités de l'ontologie et de son instanciation ont pu être définies. Cette conception a été croisée dans la théorie par l'étude de la norme ISO 15686-5, cadrant l'ontologie modélisée.
Étape 5 : Évaluation de la conception	Cette étape a été réalisée dans un premier temps par un test de fonctionnalité de l'ontologie avec des données fictives, correspondant à une évaluation Ex-Ante, avant son instanciation. Aussi, un second sondage a été réalisé afin de confirmer les problèmes et besoins, cette fois-ci liés à l'utilisation des nouvelles technologies afin de s'assurer de la pertinence de l'artefact conçu.
Étape 6 : Développement de l'artefact	L'ontologie a été instanciée dans la forme d'une plateforme fondée sur une base de données d'un graphe de connaissances (KGDB), utilisant l'ontologie et le BIM. Le développement a été réalisé en s'assurant de répondre aux besoins définis à l'étape précédente.
Étape 7 : Évaluation de l'artefact	La plateforme a été testée avec deux projets existants dont les estimations du coût de construction étaient disponibles. Les estimations des coûts d'exploitation et fin de vie ont été réalisées par nous-même sans vérification, car les résultats n'avaient aucune incidence sur la vérification du bon fonctionnement de l'artefact. La validation a donc été de type artificielle et Ex Post, basée sur une démonstration et un test avec un scénario réaliste. Cette évaluation a aussi permis de s'assurer du respect des lignes directrices de la norme ISO 15686-5.
Étape 8 : Communication des résultats	Pour finaliser le projet en bonne et due forme, l'ontologie créée a été partagée et mise à disposition en libre accès afin de partager les résultats et permettre son utilisation et modification pour tout travail futur.

5.2.2 Limites méthodologiques

La conduite de ce projet doctoral a fait face à quelques obstacles qui ont nécessité une adaptation méthodologique au cours de son déroulement. La plus grande limite rencontrée s'est trouvée au niveau de la collecte de données. Aucun projet connu au moment du déroulement de cette thèse n'entreprenait d'ACG, impliquant donc la nécessité d'une étude exploratoire afin d'en connaître l'état d'application. Nous nous sommes rapidement heurtés à la difficulté de trouver des experts de l'approche, limitant la taille de l'échantillon de l'étude. Bien que cette limite exprime déjà un résultat sur le manque de pratique, la collecte a été réitérée sous plusieurs formes (sondages, entrevues, groupe de réflexion) de manière à obtenir des résultats pertinents grâce à leur triangulation. Le second obstacle qui a grandement influencé la recherche est le manque de maturité technologique. L'entreprise accompagnée étant le plus grand donneur d'ouvrage du Québec témoigne des difficultés d'adoption du BIM. En effet, elle n'est à l'heure actuelle qu'en phase de développement du BIM 5D et n'est qu'à une étape de déploiement de l'usage d'extraction des quantités. Par conséquent, il n'a pas été possible d'intégrer un projet pour tester l'artefact avec un projet réel. La validation de l'artefact a dû être réalisée de manière artificielle, permettant de proposer une preuve de concept de la solution envisagée.

5.3 Discussion sur les résultats

Les résultats de la recherche sont la proposition d'une théorie repositionnant les experts en coûts comme meneurs idéals du coût global, la proposition d'une ontologie comme solution d'opérationnalisation, et la démonstration de son intégration dans la gestion des coût d'un projet de construction. Pour finaliser l'application de la RSC, une appréciation de ces résultats, présentée dans Tableau 5.2, est nécessaire selon les critères définis précédemment dans le Tableau 1.4.

Tableau 5.2 Application des critères de validation des résultats de la recherche

1- Congruence : Fidélité d'instanciation des principes de conception et théories.	La congruence a été respectée en suivant les principes de l'approche adaptée de la RSC basée sur les ontologies de (Nguyen et al., 2019), suivant un processus itératif et évolutif de l'ontologie. À chaque itération, nous nous sommes notamment assuré que la théorie modélisée était en adéquation et cohérente avec la norme ISO 15686-5 et la littérature.
2- Critères : Conformité de l'artefact avec les objectifs.	<p>L'objectif de cette thèse est d'explorer l'utilisation des technologies sémantiques et du BIM comme outils pour soutenir l'intégration systématique du coût global dans les pratiques d'estimation. Le premier sous-objectif est le développement d'une approche dynamique du coût global compatible avec le BIM et basée sur les technologies sémantiques. Le second sous-objectif vise à comprendre les mécanismes des projets au niveau humain, afin d'identifier des leviers qui faciliteront l'adoption du coût global.</p> <p>Des critères de conformités ont donc été déduits pour évaluer empiriquement la correspondance entre l'artefact développé et les objectifs initiaux. Cette validation s'est appuyée sur l'observation de la capacité de l'outil à :</p> <ul style="list-style-type: none"> - Intégrer et interpréter des données réelles d'estimations issues de projets, - Reproduire les processus de calcul du coût global à partir d'informations disponibles dans les maquettes BIM et les fichiers Excel, - Permettre aux professionnels de réaliser des analyses et comparaisons de scénarios de manière autonome. <p>Les observations issues de l'étude de cas de l'article 03 ont confirmé que la plateforme remplit les fonctions attendues.</p>
3- Mesures : La mesure de l'accordance de l'artefact avec les objectifs.	<p>L'accordance de l'artefact avec les objectifs a été évaluée en vérifiant sa capacité à produire des résultats cohérents avec les attentes définies, centrée sur sa capacité à exécuter correctement les exploitations attendues du calcul en coût global. La mesure porte les éléments suivants :</p> <ul style="list-style-type: none"> - La capacité de la plateforme à ingérer des données d'estimation provenant de différentes phases du projet ; - Sa capacité à générer automatiquement un coût global complet à partir de ces données ; - Sa capacité à modifier les paramètres de calcul et à produire instantanément différents scénarios et la comparaison d'alternatives. <p>Cette validation a reposé sur l'exécution de l'artefact dans un contexte contrôlé, afin de vérifier que chaque étape du processus fonctionne comme prévu.</p>

Tableau 5.2 Application des critères de validation des résultats de la recherche (suite)

4- Données d'entrée : L'utilisation de données d'entrées adaptées à l'artefact.	Les données d'entrées ont été principalement la norme ISO 15686-5, et les besoins des estimateurs et économistes qui ont été exprimés dans le groupe de réflexion. Du côté pratique, les données à entrer dans l'artefact correspondent au niveau de maturité technologique observé dans la pratique, c.-à-d. un modèle IFC et des fichiers de calcul Excel encore grandement utilisés par les experts en coûts.
5- Conception de l'artefact : Conception d'un artefact dont les composants sont cohérents et explicables.	L'artefact a été basé dans un premier temps sur la conception de l'ontologie par la complétion d'une fiche de spécification avec le groupe de réflexion telle que présenté dans l'article 02. La conception de l'instanciation de l'ontologie a été réalisée en fonction des besoins exprimés par ce même groupe. Finalement, le fonctionnement de l'artefact a été conçu pour s'accorder avec la maturité technologique actuellement observée dans les organisations. Cette adéquation repose sur les constats tirés de l'accompagnement au déploiement du BIM au sein du département Estimation de la SQI, où les pratiques reposent encore largement sur l'utilisation de fichiers Excel pour la production des estimations, et dont le principal usage en déploiement était l'extraction de quantités à partir des modèles IFC.
6- Langage : Utilisation d'un langage approprié pour rendre l'artefact accessible et utile.	Basé sur la norme ISO15686-5, l'artefact respecte le vocabulaire de cette norme afin de permettre une compréhension commune des concepts.
7- Améliorations relatives : Améliorations d'un artefact par rapport à un autre similaire.	Les contributions présentées de l'artefact combler des lacunes de la littérature. En effet, au moment de la publication de l'article 02, aucune ontologie récente et complète sur le coût global n'avait été proposée. Concernant la plateforme sémantique, une autre étude proposait un artefact similaire mais seulement pour une application au niveau de la gestion de portefeuilles. Notre artefact vient donc en complément, se concentrant sur l'aspect opérationnel du coût global.
8- Représentativité : Fidélité de l'artefact dans la représentation de la réalité.	L'artefact a été conçu en s'appuyant directement sur les pratiques observées, le contexte d'application et le contexte théorique de la recherche. La conception repose sur les besoins opérationnels exprimés par les estimateurs lors du groupe de réflexion, dans l'article 02, et sur les pratiques réelles d'estimation analysées dans l'article 01. Les données d'entrée utilisées pour l'instanciation reflètent le niveau de maturité technologique actuellement observé au Québec. L'ensemble de ces éléments assure que l'artefact représente fidèlement la manière dont le coût global est effectivement réalisé dans la pratique, tout en intégrant les concepts normatifs de l'ISO 15686-5.

Tableau 5.2 Application des critères de validation des résultats de la recherche (suite)

9- Exigences : Satisfaction de l'artefact avec les besoins de la recherche et la pratique.	La validité des exigences a été assurée en croisant deux sources complémentaires. D'une part, la revue systématique de la littérature présentée dans l'article en ANNEXE I a permis d'identifier les besoins théoriques liés au coût global dans le contexte des travaux récents cherchant à articuler BIM et coût global. D'autre part, ces exigences ont été ajustées à partir des attentes concrètes exprimées par les professionnels lors du groupe de réflexion (article 02). L'artefact a ainsi été conçu pour répondre simultanément aux exigences issues de la recherche et aux besoins opérationnels de la pratique.
10- Théories : Justification de la théorie.	Les connaissances du coût global représentées du coût global correspondent à celles de la norme ISO 15686-5 et ont été étendues dans l'instanciation pour correspondre aux besoins de la pratique.

Bien que chacun des critères ait été respecté dans la mesure du possible, il convient de souligner que la taille limitée de l'échantillon et la rareté des projets mobilisables limitent la portée de la validation. Ces contraintes affectent particulièrement les critères de représentativité, d'exigences et de mesures, qui reposent sur un nombre restreint de participants et de cas d'application. L'artefact n'a pu être testé que sur deux projets dans un contexte artificiel, et non sur des cas réels intégrant toutes les phases du cycle de vie. Cette limite s'explique par le manque de maturité de la pratique du coût global et du BIM dans l'industrie québécoise, témoignant néanmoins de la difficulté d'application de l'approche. Dans le cadre de cette recherche doctorale, ce type de validation artificielle reste cohérent avec l'approche de la RSC. Les résultats doivent ainsi être interprétés comme une preuve de concept, démontrant la faisabilité de l'approche proposée, plutôt que comme une validation généralisable à l'ensemble du secteur. Cette limite met en évidence un besoin de validations complémentaires, avec davantage de projets réels et d'experts, afin d'ancrer les résultats.

5.4 Originalité et contributions

La RSC permet d'assurer un travail original et contribuant à la fois au niveau pratique et théorique. Au niveau pratique, une ontologie du coût global a été produite, offrant un cadre de connaissance utilisable pour la construction de solutions logicielles avec des capacités de raisonnement sémantiques. L'originalité de ce travail est également soutenue par la prise en compte du contexte global, garantissant une intégration pertinente de la solution dans les pratiques réelles. Cette recherche se distingue des travaux existants par plusieurs aspects. Alors que la plupart des solutions proposées reposent sur des logiciels propriétaires et natifs, l'approche développée ici est agnostique, fondée sur l'utilisation des maquettes IFC et proposée sous la forme d'une plateforme open source. Contrairement aux ontologies déjà publiées, qui ne sont généralement ni spécifiques au coût global ni alignées sur la norme ISO 15686-5, l'ontologie proposée formalise directement cette approche à partir des normes existantes.

L'instanciation de cette ontologie a donné lieu à l'élaboration d'une plateforme sémantique à destination des estimateurs et économistes, permettant l'analyse automatique d'estimations afin d'interpréter les impacts des conceptions sur le coût du cycle de vie des projets. L'ontologie aurait pu permettre bien des fonctionnalités différentes par sa flexibilité d'application. En effet, une ontologie peut être utilisée pour différents usages tel que la validation d'informations de modèles, l'harmonisation du vocabulaire utilisé dans un projet, ou encore alimenter des algorithmes spécifiques (McGuinness, 2003). De même le niveau de technicité de la solution aurait pu être plus avancé avec des fonctionnalités d'estimation automatiques. Cependant, le niveau de maturité de l'industrie est encore trop peu développé aujourd'hui pour ce type de solution. Les professionnels sont encore à l'aube de l'adoption systématique du BIM, qui est au centre de l'avancement technologique du secteur. Les nombreux cas d'usage qu'il offre sont encore peu maîtrisés par les praticiens. C'est particulièrement le cas pour l'estimation des coûts basés sur le BIM. Tel qu'introduit dans cette thèse, un effort est encore nécessaire pour maîtriser le BIM et ses procédés, qui sont notamment ralentis par un manque de compréhension des requis informationnels. Cela

justifie donc le niveau technique de l'instanciation proposée, qui pour plus de fonctionnalités, nécessiterait l'étude de ces exigences pour les intégrer. Ce point sera développé plus loin dans les travaux futurs.

La contribution de cette instanciation est une approche de l'ACG pour les estimateurs et économistes. La plateforme développée à partir de l'ontologie, permet un calcul automatique du coût global, mais aussi la possibilité d'interpréter les résultats selon les conceptions réalisées et sous les différentes perspectives des acteurs impliqués. De plus, bien que ne proposant pas d'analyse de risque explicite, le système proposé permet de modifier chaque paramètre pour en voir automatiquement les impacts sur les résultats. L'utilisateur peut donc réaliser des analyses de sensibilité et enregistrer pour comparaisons différents scénarios.

L'un des problèmes soulevés de la littérature quant aux recherches doctorales utilisant la RSC, est le manque de contribution théoriques (Cater-Steel, Toleman, & Rajaeian, 2019b). Gregor et Hevner (2013), identifient différents niveaux de contributions à la recherche, allant des instanciations spécifiques pour une situation, établissant un savoir peu mature, à un concept abstrait développant une théorie à propos d'un phénomène, décrivant un savoir mature et ancré (Gregor & Hevner, 2013a). Les mêmes auteurs ont développé un cadre permettant de positionner la contribution théorique des recherches utilisant la RSC. Selon le cadre, quatre types de contributions existent (Gregor & Hevner, 2013a):

- L'invention, reflétant le résultat de nouvelles solutions conçues pour de nouveaux problèmes identifiés. Cette catégorie présente des résultats avec des solutions et un domaine d'application peu mature.
- L'amélioration, présentant des résultats de nouvelles solutions pour des problèmes connus. Cette catégorie présente des résultats avec des solutions peu matures mais un domaine d'application mature.
- L'exaptation, apportant des solutions connues pour des nouveaux problèmes. Cette catégorie présente des résultats avec des solutions matures mais un domaine d'application peu mature.

- La conception de routine, appliquant des solutions connues pour des problèmes connus, ne proposant donc aucune contribution majeure. Cette catégorie présente des résultats avec des solutions et un domaine d'application arrivés à maturité.

L'instanciation proposée est d'un niveau bas de maturité de connaissance, car elle a été conçue pour répondre à un usage précis et testée dans un contexte limité. Selon les critères du cadre de Gregor et Hevner, une contribution de faible maturité se caractérise par une solution encore spécifique, non généralisée et validée sur un nombre restreint de cas. Or, l'ensemble de la recherche permet une contribution plus aboutie à la connaissance sur le coût global. En effet, un problème bien connu ne signifie pas un problème bien compris. La recherche menée s'est avérée être un travail plus profond que la simple conception d'un outil du coût global. Les problèmes persistants de l'approche, qui font qu'elle n'a jusqu'ici jamais été ancrée dans les pratiques, a nécessité l'investigation de l'état d'application du coût global pour comprendre comment il peut s'intégrer dans ce contexte de transition numérique. La thèse contribue ainsi à la théorie par cette mise à jour de l'état d'application de l'approche dans l'industrie. Nous identifions la contribution de cette thèse comme une amélioration, qui a utilisé une solution connue mais encore immature pour le secteur, pour un problème connu.

Plus encore, la proposition d'une ontologie comme solution a démontré une avenue particulièrement adaptée pour le contexte étudié. Cette démarche a nécessité de reprendre comme point de départ l'étude des concepts de base du coût global afin d'en proposer une représentation formelle adaptée à son contexte d'application. Ainsi, l'ontologie garde l'essentiel applicable au domaine de connaissances pour servir de solution répondant au problème et adapté au contexte. L'ontologie reste flexible et modifiable afin d'ajouter ou modifier des concepts selon l'évolution du contexte. Le résultat de son instanciation présente une démonstration des bénéfices des technologies sémantiques pour le secteur de la construction. Les résultats de cette thèse contribuent à l'évolution de la maturité de l'application de solutions basées sur des ontologies.

5.5 Diffusion des résultats

Afin de diffuser les résultats, nous avons mis en œuvre les moyens nécessaires pour assurer le suivi de son impact. Pour assurer une diffusion visible de notre ontologie, nous avons choisi de la publier en suivant les principes FAIR. Les principes FAIR, issus d'un atelier de conception collaborative entre différents acteurs issus de la recherche et du milieu professionnel, ont pour but de supprimer les obstacles à l'accessibilité et à la réutilisation des données. FAIR désigne les principes suivants (Wilkinson et al., 2016):

- F : Findable (Découvrable)
- A : Accessible (Accessible)
- I : Interoperable (Interopérable)
- R : Reusable (Réutilisable)

Respectant ces principes, nous avons décidé de publier l'ontologie sur le site Zenodo.org, permettant d'obtenir un Digital Object Identifier (DOI), facilitant sa citation. De plus, la publication offre la possibilité de suivre le nombre de vues et de téléchargements de l'ontologie, offrant des indicateurs clairs pour suivre l'intérêt envers celle-ci. L'ontologie est disponible au lien suivant : <https://doi.org/10.5281/zenodo.16747582> (Adam Yousfi, 2025).

En complément, l'instanciation de l'artefact a été rendue accessible sur la plateforme GitHub afin de laisser la possibilité aux intéressés de tester l'approche. Le lien vers la plateforme est le suivant : <https://github.com/AdamY76/WLC-PLATFORM-ETS>

5.6 Travaux futurs

5.6.1 Travail sur l'approche en coût global

Avant toute recommandation de développement de nouveaux outils ou approches, il est suggéré de multiplier l'utilisation du coût global dans les projets, et ce particulièrement au Québec qui ne dénombre que peu d'exemples d'application. Comme discuté dans cette thèse,

l'ACG englobe un grand nombre d'incertitudes, qui sont surtout aujourd'hui des inconnues étant donné le manque de pratique. Ainsi, apporter plus d'exemples d'utilisation permettra de mieux comprendre la prédiction du coût global, ses facteurs d'influence selon le contexte local, les paramètres choisis ou encore les types de projet. Cela permettrait de faire évoluer les ACG qui reposent encore largement sur des scénarios déterministes, alors que les décideurs adaptent leurs choix selon les circonstances du projet. Il sera important de voir comment notre plateforme peut s'intégrer dans les processus de décision pour les rendre plus flexibles et de mieux refléter la dynamique réelle des projets.

Une autre dimension qui sera capital d'approfondir concerne le point de vue retenu pour l'ACG. La solution proposée dans cette thèse offre une vue multi parties des coûts, supposant que l'expert en coût responsable de l'ACG soit capable de se positionner selon différents points de vue pour déterminer les implications des coûts pour chaque acteur présent dans le projet, ou du moins les plus importants. Cette approche ne résout donc pas la question, mais fait de l'expert en coût l'utilisateur principal, et selon les demandes, il pourra intégrer différentes perspectives de l'ACG. De futurs travaux pourront évaluer ces différentes visions des coûts pour définir et comparer des facteurs d'influences propres à chacun, afin de guider la manière de mener l'ACG en termes méthodologiques, paramétriques et interprétatifs. Ainsi, l'artefact pourra être amené à évoluer pour intégrer ces aspects et préciser les analyses.

Pour cela, des travaux menés par des approches de recherche appliquée telles que la RSC ou la recherche action, cadrant des études de cas, apporteront des éléments importants pour faire évoluer l'application de l'approche. Plus encore, cela permettrait de répertorier des données essentielles telle que la durée de vie des éléments dont les bases de données sont encore émergentes et peu documentées. Ces études appliquées offriraient non seulement un retour d'expérience opérationnel, mais aussi une base empirique indispensable pour enrichir les bases de données existantes et consolider les standards de l'approche. Ces actions permettront de mieux cerner les exigences d'informations, ce qui facilitera la voie pour l'utilisation de nouvelles technologies et du BIM pour cet usage.

5.6.2 La transformation organisationnelle et l'évolution du rôle de l'expert en coût

Les résultats de l'étude soulignent aussi que le manque de données et de collaboration dans les projets constitue des freins majeurs à l'intégration du coût global. Dans une certaine mesure, ces deux dimensions sont liées, du fait que l'absence de données est souvent la conséquence d'une fragmentation organisationnelle où chaque acteur produit et conserve l'information selon ses propres objectifs. Dans ce contexte, le rôle proposé dans cette thèse pour l'expert en coûts ne doit pas être compris comme une responsabilité isolée, mais comme une fonction d'orchestration. Il devient un acteur transversal, capable de structurer les échanges, de formaliser les hypothèses communes et de coordonner les contributions des différentes parties prenantes. Cette évolution suppose une montée en compétences relationnelles et stratégiques, au-delà de la maîtrise technique des calculs.

Il conviendra inéluctablement de pousser les résultats de cette étude vers des cas d'application afin de voir comment l'ACG peut s'intégrer de manière collaborative dans les projets pour en exploiter son potentiel. En plus du BIM, l'émergence de nouveaux modes contractuels collaboratifs, tels que les modes de réalisation de projet intégrée ou les livres ouverts, pourrait porter cette transformation. Ces cadres favorisent le partage des risques, la collaboration et la transparence des données dès les phases amont des projets.

Dans cette perspective, le rôle de l'expert en coûts, tel que défini dans cette recherche, devra être cartographié en interaction avec ceux des autres parties prenantes afin d'identifier clairement les responsabilités informationnelles de chacun. Une telle cartographie de l'ACG permettra de déterminer ses exigences en termes d'échanges d'informations et de clarifier son intégration organisationnelle dans les projets.

5.6.3 Le déploiement des nouvelles technologies pour soutenir le coût global

Comme démontré dans cette thèse, la déclinaison de l'ontologie, constitue une avenue importante pour des travaux futurs. Elle pourra passer par l'extension ou la modification des concepts et relations présents dans l'ontologie, ou encore sa liaison avec d'autres ontologies.

Ce travail pourra être réalisé dans un premier temps afin d'en étendre les capacités de raisonnement pour répondre à d'autres besoins tels que la connexion à des bases de données ou soutenir des prises de décisions liées aux activités de maintenance.

Aussi, l'autre perspective serait d'étendre directement l'instanciation proposée en termes de données liées. En effet, la plateforme sémantique a été ici conçue spécifiquement pour les données ouvertes, à savoir des modèles IFC et des estimations en format .xls. Néanmoins, s'il advenait que des utilisateurs souhaitent l'utilisation de données de formats spécifiques, un travail de programmation serait nécessaire pour associer les instances de l'ontologie à ces formats. Cela n'enlève pas le bénéfice de l'ontologie, car ce travail n'est à faire qu'une seule fois pour chaque format de fichier souhaité.

L'utilisation des ontologies facilite donc l'accès aux données, et lorsqu'elle en est peuplée, elle devient un graphe de données. Comparativement à une base de données classique, dont les données sont fixes, les données des graphes sont facilement accessibles et par-dessus tout dynamiques. En effet, elles peuvent être mises à jour en temps réel selon les fichiers auxquels ils sont liés. Ainsi, elles peuvent être utilisées comme outil d'agrégation de données afin d'alimenter des bases de données pour stockage si besoin, mais surtout des modèles en temps réel ou encore comme présenté dans l'instanciation de cette thèse, alimenter des algorithmes. Ces graphes pourraient, par exemple, permettre de suivre en continu l'évolution des coûts de maintenance associés aux équipements. À la vue des tendances de recherche actuel, les travaux futurs se dirigeront vers l'optimisation de l'utilisation de ces données, ouvrant naturellement la voie aux outils d'intelligence artificielle. Une perspective prometteuse réside dans l'utilisation de techniques d'apprentissage automatique, exploitant les graphes de données issues de projets passés pour prédire la durée de vie d'éléments, anticiper des dépassements de budget ou proposer des stratégies de remplacement optimisées. Ces pistes devront toutefois être explorées en tenant compte des exigences d'information propres au coût global, afin de garantir la robustesse et la pertinence des résultats générés.

5.6.4 L'utilisation des ontologies pour le développement d'un coût global durable

Tel que démontré dans l'article 02, les ontologies ont la possibilité d'être étendue avec d'autres ontologies possédant des concepts communs. Ainsi, il est possible de créer des instanciations avec des fonctionnalités plus étendues selon les objectifs de l'analyste. Les travaux futurs pourront servir à l'exploration de l'alignement de cette ontologie avec d'autres représentant de concepts liés à la durabilité, tels qu'identifié dans l'article en ANNEXE I. Des concepts tels que l'analyse en cycle de vie, l'économie circulaire ou encore l'analyse de la valeur pourront être couplés dans des travaux futurs utilisant l'alignement de notre ontologie avec ces ontologies respectives. Tel que présenté dans le rapport mentionné en partie 1.8.5, l'économie circulaire s'avère être un concept particulièrement adapté pour compléter la vision systémique du coût global. L'ACG permet d'explicitier et d'optimiser les coûts sur tout le cycle de vie d'un projet, tandis que l'économie circulaire valorise la réutilisation, la réparation et le recyclage des ressources. Leur combinaison aide à démontrer que les choix circulaires ne sont pas seulement écologiques mais aussi économiquement viables. Un « coût global circulaire » pourrait être défini comme une analyse holistique des coûts pertinents du cycle de vie, visant à analyser des scénarios pour prolonger la durée de vie d'un projet et à transformer les externalités négatives en positives. Cette approche pourrait apporter des opportunités pour l'optimisation de l'usage des ressources et des investissements, notamment en considérant les déchets et ressources de fin de vie doivent être considérés comme de nouvelles sources de valeur. Ainsi, de futurs travaux devraient explorer comment créer un environnement favorable à l'économie circulaire grâce au coût global, investissant sur l'impact de ce dernier sur la sensibilisation, la formation et la création d'incitations fiscales. D'un point de vue technologique, l'artefact de cette thèse pourrait être réutilisé pour compléter des ontologies liées à des concepts durables, permettant d'analyser les coûts associés à des stratégies de réemploi, de recyclage ou d'économie circulaire, et de relier ainsi les dimensions économiques et environnementales pour soutenir les prises de décisions.

5.7 Réflexions finales sur le coût global

Pendant la réalisation des entretiens semi-structurés, plusieurs professionnels apportaient des réflexions intéressantes, et surtout importantes pour la philosophie même de l'ACG. Le tableau ci-dessous présente des citations issues de professionnels, que nous essayons ici d'interpréter afin de couvrir l'entièreté des enjeux du coût global, permettant de remettre en contexte la recherche à tous ses niveaux.

Tableau 5.3 Réflexions sur l'approche du coût global d'après des citations issues des entretiens semi-dirigés

Citation	Contexte et interprétation
« Il y aurait un intérêt, mais il doit y avoir une volonté d'avoir cet intérêt » - anonyme, économiste dans une institution publique.	L'économiste insinuait ici que les politiques pourraient avoir un intérêt si leur mandat couvrait la durée de vie des constructions. Cet enjeu dans le milieu public soulève un questionnement culturel, et le besoin de travailler sur des stratégies de gouvernance à long terme.
« Si pour le cycle de vie, il y a un début, il y a une fin, c'est défini, et ensuite c'est accepté par tout le monde, alors il y a certainement de l'intérêt pour coût global. » - anonyme, économiste dans une institution publique.	Le professionnel exprimait le besoin que tous soient impliqués dans la définition de la durée de vie du projet. Cette citation révèle un enjeu organisationnel pour la mise en place du coût global. Il convient donc de traiter l'aspect contractuel, et de développer des cadres de responsabilités clairs pour faciliter son utilisation.
« Si vous n'avez pas de données, cela signifie que vous n'avez aucune idée de la tenue de votre structure dans le temps, si elle devra être maintenue dans 15, 20 ou 25 ans. Vous dites simplement que théoriquement c'est bon pour 25 ans, et en fait, vous n'en avez aucune idée. » - anonyme, analyste environnemental dans une firme de génie-conseil	Cette remarque rappelle que construire sans connaître les implications relève d'un manque de responsabilité de la part de l'investisseur. Cela souligne l'importance de rassembler des données, de construire des bases de données qui vont supporter la maîtrise des infrastructures, et surtout la construction durable.

Tableau 5.3 Réflexions sur l'approche du coût global d'après des citations issues des entretiens semi-dirigés (suite)

<p>« En fait, je pense que le coût global peut être un très bon outil pour montrer les besoins. » - anonyme, gestionnaire d'actif dans une institution publique</p>	<p>L'ACG permet d'anticiper l'avenir et d'élaborer des plans financiers. Cela renforce l'idée de travailler sur le coût global en tant qu'outil d'interprétation et explorer son utilisation pour encourager une communication transparente entre les acteurs des projets.</p>
<p>« S'il y a un coût environnemental, c'est qu'il y a déjà une externalité, mais on pourrait y penser en amont. » - anonyme, expert en économie de l'environnement</p>	<p>Il est aujourd'hui admis que chaque problème environnemental doit être traité afin d'éviter leur accumulation. Il est donc primordial de les anticiper pour éviter des surcoûts de remise en condition. Le coût global étendu doit donc continuer à être mis de l'avant pour faciliter la maîtrise de ces coûts.</p>
<p>« Lorsque nous faisons une estimation des travaux, nous avons un engagement sur ces prix, si le client commence à nous demander des coûts environnementaux et/ou futurs alors cela devient compliqué pour nous. » - anonyme, économiste dans une entreprise de construction générale</p>	<p>Cette remarque montre qu'il est primordial de partager les risques, non pas pour effectuer le calcul, mais pour formaliser les prévisions afin d'avoir de la transparence et éviter des imprévus. Cette citation souligne de nouveau le besoin de développer des cadres clairs sur la responsabilité des parties prenantes.</p>
<p>« Les coûts de construction sont considérés comme plus importants car c'est là que se trouvent les gros montants. » - anonyme, économiste dans une entreprise de construction générale</p>	<p>Cette citation exprime la cause principale du désintérêt de la pensée en cycle de vie et pourquoi la demande du client d'analyse en coût global est très faible. Les enjeux financiers sont plus importants à l'investissement car il y a plus à perdre au lancement du projet. Ceci montre l'importance de travailler sur des incitatifs pour changer ces pratiques.</p>

Ces citations directement issues des témoignages démontrent qu'il existe des enjeux profonds au niveau du paradigme de la pensée en cycle de vie. Si une conscience de l'importance d'une vision à long terme est présente, les freins observés relèvent surtout des barrières culturelles et organisationnelles. Les professionnels expriment ainsi un besoin de soutien institutionnel et contractuel pour s'engager dans une telle démarche. La thèse proposée confirme que des solutions techniques existent, mais que leur adoption dépendra avant tout

d'une amélioration au niveau de la gouvernance, la formation et les incitations mises en place.

CONCLUSION

À travers cette thèse, nous avons proposé l'étude de l'approche du coût global dans le contexte d'une industrie de la construction en phase de profonds changements technologiques. L'arrivée des nouvelles technologies de l'information, menées par le BIM, promet une amélioration des pratiques, y compris celles d'estimation des coûts. Néanmoins, des défis environnementaux et socio-économiques soumettent le secteur à des enjeux majeurs impliquant un besoin de maîtriser les impacts des constructions sur l'ensemble de leur cycle de vie, exercice encore peu courant. L'ACG a souvent été étudiée et formalisée dans la théorie, mais elle se révèle peu documentée dans la pratique. Dans ce contexte, l'objectif de cette thèse était d'explorer l'utilisation des technologies sémantiques et du BIM comme outils pour soutenir l'intégration systématique du coût global dans les pratiques d'estimation. L'objectif a été atteint en répondant à la question de recherche suivante : *Quelles opportunités offrent le contexte socio-technologique actuel des projets de construction pour adopter le coût global dans les pratiques d'estimation ?*

L'article 01 met en avant l'aspect humain de l'adoption du coût global. Les barrières souvent répétées dans la littérature ont été confirmées sur le terrain, et l'analyse a mis en évidence que l'approche reste mise de côté car il manque un meneur assumant la responsabilité de la tâche. Cette recherche propose que les estimateurs et économistes de la construction endossent cette responsabilité, en intégrant le coût global comme un mode de pensée au cœur de leurs pratiques professionnelles. L'instanciation présentée dans l'article 03 a montré qu'une plateforme fondée sur une ontologie, présentée dans l'article 02, et connectée au BIM permet d'automatiser le calcul du coût global, de faciliter l'exploration de scénarios et d'assurer l'interopérabilité des données. Cette preuve de concept illustre que le coût global peut être intégré de manière fluide dans les pratiques numériques actuelles, ouvrant la voie à des usages plus avancés.

La thèse démontre aussi qu'une solution rigoureuse nécessite avant tout une compréhension de son contexte d'intégration. En cela, l'ontologie s'avère particulièrement adaptée pour

formaliser les concepts du coût global dans le contexte d'un projet de construction. L'approche proposée permet d'assurer une interopérabilité entre les différentes sources de données, assurant leur bonne intégration. Elle favorise également un raisonnement automatique et évolutif, garantissant l'adaptation de la solution aux besoins futurs. Aussi, le réel succès sera de faire vivre le coût global dans les pratiques, et donc de proposer des outils en phase avec les habitudes des praticiens pour qu'il fasse partie des activités quotidiennes des projets.

Les limites de cette recherche résident principalement au niveau du contexte de l'étude. La rareté des experts et des projets intégrant le coût global au Québec a restreint la taille de l'échantillon et conduit à une validation de l'artefact en contexte artificiel. Ces contraintes situent la thèse au niveau d'une preuve de concept. Les contributions principales du travail se situent à deux niveaux. Sur le plan pratique, la thèse propose un outil conceptuel et technique permettant aux estimateurs et économistes d'intégrer le coût global dans leurs activités courantes, en facilitant l'analyse, la comparaison de scénarios et l'interopérabilité avec le BIM. Sur le plan théorique, elle repositionne le rôle de ces professionnels comme porteurs de l'approche et formalise un cadre conceptuel standardisé basé sur la norme ISO 15686-5. Ces apports renforcent la capacité de la recherche à fournir une base commune et réutilisable, tout en offrant aux praticiens un levier concret pour améliorer la prise de décision économique, environnementale et sociale dans les projets.

Ce travail ouvre plusieurs perspectives pour de futurs travaux de recherche. Dans un premier temps, la multiplication des cas d'application concrets du coût global dans les projets, menés dans le cadre de démarches de recherche appliquée permettra d'élargir la taille des échantillons et de constituer des bases de connaissances plus précises, notamment sur les durées de vie et autres paramètres encore peu documentés. Une extension de l'ontologie pourra être envisagée afin de couvrir des besoins spécifiques tels que l'optimisation des consommations, tout en renforçant son interopérabilité avec différents formats et bases de données. Il sera important d'explorer l'utilisation de techniques d'apprentissage automatique pour exploiter leurs capacités de prédiction. Enfin, ces travaux futurs devront aussi

s'intéresser aux changements organisationnels qu'impliquerait l'adoption systématique du coût global, en particulier le repositionnement des estimateurs comme acteurs clés de son interprétation et de sa diffusion.

Le secteur de la construction se trouve à un moment charnière. Cette thèse montre que le coût global, longtemps cantonné à des approches théoriques, peut être rendu opérationnel grâce aux technologies numériques et aux pratiques collaboratives. La contribution majeure réside dans l'établissement des fondements conceptuels et techniques pour une intégration complète du coût global dans le contexte de la transition numérique du secteur. Il est toutefois souligné que son adoption dépendra d'une évolution culturelle et organisationnelle où estimateurs et économistes auront l'occasion de monter en compétences et d'apporter une valeur ajoutée supplémentaire aux projets, en optimisant les décisions financières sur les plans économique, environnemental et social.

ANNEXE I

EXPLORING THE SYNERGIES BETWEEN LIFE CYCLE COST / WHOLE LIFE COST AND BUILDING INFORMATION MODELING: A SYSTEMATIC LITERATURE REVIEW

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Abstract

Life Cycle Costing (LCC) is a cost estimating approach for project and asset planning and delivery that considers the direct and indirect costs incurred over the entire life cycle of an asset. This approach can be expanded to the concept of Whole Life Cost (WLC), which in addition to LCC considers externalities and benefits. WLC can demonstrate the financial impacts, both positive and negative, of a project on its environment, in other words it can show its complete value. Despite its potential, the approach is still perceived as complex because, among other things, access to data can be difficult and the approach is still not supported by a standardized methodology. Building Information Modeling (BIM) could be used to address these issues as both WLC and BIM are deemed complementary. Indeed, their synergies are linked to decision making, project understanding and life cycle thinking. BIM provides WLC with better data management, improved calculation accuracy and visualization of project impacts. In return, WLC improves project understanding, decision making and reinforces life cycle thinking. This paper aims to study the potential synergies

between BIM and WLC through a systematic literature review. The identification of these synergies helped form a frame of reference to better understand the opportunities that this combination can offer. Future studies would be needed to explore the application of BIM and WLC at different project scales and identify the context in which the combination of BIM and WLC is the most beneficial.

Keywords

BIM, Life Cycle Cost, Whole Life Cost

1. Introduction

Capital investments in construction are typically based on initial purchase cost. This focus on up-front costs hinders innovation, especially ecological innovations, whose higher investment cost is a major barrier to their implementation in projects. Thus, opportunities for both the project and the investor might be missed due to a lack of long-term investment and financing of projects and real property assets (Kaenzig and Wüstenhagen 2009). Nowadays, it is widely known that initial costs represent only a small proportion of the costs of a building, compared to the operating and end-of-life costs. It is also known that choices made in the early phases can have the most impact on the entire project (Liu *et al.* 2015, Jausovec and Sitar 2019, Rashed *et al.* 2019, Rad *et al.* 2021). In this context, Life Cycle Costing (LCC) appears as a relevant solution to ensure that the best choices are made to generate value for an asset. LCC is defined by ISO 15686-5 as the “*cost of an asset or its parts throughout its life cycle, while fulfilling the performance requirements*”, and its function is to quantify life cycle costs to support decision making and evaluation processes. Thus, the LCC can not only help to estimate capital expenditures but also estimate and control future expenditures, a nuance that makes it possible to find the best compromises to optimize the cost of a project asset across its entire life cycle (Farr and Faber 2018). The estimation can be made more complete and more accurate with a Whole Life Costing (WLC) approach, introduced by ISO 15686-5 as “*all significant and relevant initial and future costs and benefits of an asset, throughout its life cycle, while fulfilling the performance requirements*”.

In other words, WLC includes LCC, benefits, non-construction costs and externalities that can be quantified and expressed in monetary terms (e.g., carbon emissions) (Pelzeter 2015). Owners may benefit from WLC to design projects that align with their organization's capacity to afford facility costs relating to maintenance but also to minimize environmental impacts (Pearce *et al.* 2010). Even though WLC shows great potential, certain barriers are limiting its widespread adoption, such as, the difficulty to access data and its complexity and lack of methodology (El-Haram *et al.* 2002). Recent studies have shown that BIM could help facilitate the application of WLC and overcome these barriers. However, these studies are mostly focused on practical ways to combine WLC and BIM and actual literature as to theoretical bases is still lacking. This paper aims to study the application of BIM and WLC using a systematic literature review based on this research question: What synergies do BIM and WLC share? After identifying these, we followed the methodology developed by Jabareen (2009) and created a conceptual framework. This reference framework could help to better understand the opportunities resulting from the application of both approaches for future studies.

2. Literature Review

Life cycle thinking can potentially offer real control over projects and guarantee best value for real property assets and asset portfolios. Each choice made, especially in the early lifecycle phases, will have an impact on the whole life cycle of an asset. Indeed, Mistry (2016) used LCC and Life cycle analysis (LCA) as indicators to assess the performance of a pier. It was shown that the modification of just one material had significant environmental and economic impacts on the asset's life cycle. Therefore, if an optimal result is to be achieved, it is important to consider an asset as a whole. To reiterate, ISO 15685-5 defines the main role of LCC as the quantification of life cycle costs to support decision-making and evaluation processes throughout the entire project. Because WLC enables the financial analysis of externalities, associating it with other concepts offers great opportunities to improve project quality by offering a financial point-of-view. Indeed, WLC can help in waste management , Circular Economy (Wouterszoon Jansen et al., 2020), Value for money

(Araújo, Almeida, Bragança, & Barbosa, 2016) and Target Costing (Janz et al., 2006). It also has been demonstrated that WLC is a powerful tool for negotiations and can have a positive impact on project communication if used collaboratively (Zachariassen and Arlbjørn 2011). Despite its utility, WLC still faces barriers and it is not widely used. Higham (2015) studied the barriers of LCC in the UK construction industry and revealed that the major blockage lies in the client's habit of short-term budgeting and in the lack of awareness of the benefits of the approach. Another issue reported in the literature was the subjectivity of the calculation parameters, especially for the discount rate, which has a significant impact on the forecasting process (Olubodun *et al.* 2010). This implies the possibility of over- or under-estimating the calculation assumptions (Jafari *et al.* 2014). One of the main challenges resides in data collection and management. Indeed, collecting all the data needed for the estimation can be difficult and very time-consuming. Also, data may be inexistent or inaccessible if there is no life cycle inventory available for the project (Teshnizi *et al.* 2018). Applying BIM for WLC is a new recent trend in the literature and it appears to be overcoming some of the barriers mentioned here. Indeed, BIM is seen to have the capability to automate the process of WLC and to be used as a data repository (Santos, Aguiar Costa, et al., 2020). Past research has also looked at specific applications of BIM for WLC. Lu (2021) conducted a systematic literature review (SLR) focusing on practical approaches to implement BIM for WLC. He proposed a framework describing how to integrate BIM by linking a spreadsheet, using an external platform, or directly using the BIM modeling environment. To demonstrate that BIM can enhance LCC, Altaf (2020) conducted an SLR that aimed to identify the potential for BIM in automating the LCC approach. The study resulted in a framework to calculate LCC with BIM. Moreover, while the study proposed a theoretical basis for BIM and LCC, only one database was explored. Thus, there seems to be a lack of research investigating the current trends, barriers and opportunities of BIM for WLC. The research presented in this paper addresses this gap.

3. Research Methodology

In this paper, a systematic literature review (SLR) was undertaken to identify the synergies between BIM and WLC. The SLR was performed using the following terms: (“Building Information Modelling” OR “BIM”) AND (“Life Cycle Cost” OR “Whole Life Cost” OR “LCC” OR “WLC”) inside the following databases: Scopus, ASCE, Compendex, Emerald Insight, IEE explore, Science Direct, Web of Science. For this study, peer-reviewed research articles, but also grey literature like technical reports, theses and dissertations, conference papers, committee reports, and government documents were used. Grey literature was also included and searched for in the following databases: ProQuest, Open Access Theses and Dissertations (OATD) and GLOBAL ETD. The results were limited to studies related to the application of BIM and WLC at the project scale in the construction sector. Only studies in English and French were selected. No time or location limits were set. Once the strategy was established, a PRISMA flow chart of the SLR was followed (Figure A I. 1). For the peer-reviewed documents, the key terms searched for in the mentioned databases allowed the research team to identify 1360 results that were imported into Zotero. Zotero is a reference management software that facilitates the collection and organization of references. Once duplicates were removed, a total of 932 documents remained. Each abstract was analyzed to exclude irrelevant studies, e.g., those not in English or French and those not related to the construction sector. To achieve this, excluding criteria were defined as follow: Language is not English or French, the study does not concern construction domain, the abstract does not mention a cost estimation or management of the project, the abstract does not mention that life cycle is considered, and the scope of the study does not consider the asset performance. Thus, studies about life cycle cost estimation or management of construction projects were kept for full assessment. The abstract screening process retained 119 documents, 110 of which could be retrieved and were fully assessed for eligibility. This step allowed to identify studies using BIM to conduct life cycle cost estimation or management. In the end, 81 studies were retained for the study. For grey literature, keywords had to be changed for Global ETD and OATD databases as these search engines are less elaborate, limiting the search respectively to “BIM” AND “Life cycle cost” and “BIM” OR Building information modelling” AND “Life cycle cost” OR “Whole life cost”. A total of 161 documents were identified of which 80 duplicates were removed and 9 were not accessible. Therefore, 72

documents were identified for analysis. Among these, 4 were neither in English nor in French, 11 were not in the construction sector and 49 did not involve BIM or WLC in the study. In all, 8 grey literature documents were considered, for a total of 89 documents for this SLR. The documents were then analyzed by identifying the utility and expectations of BIM to the project, the utility and expectations of WLC with regards to the project, the BIM impacts on WLC, and WLC impacts on BIM.

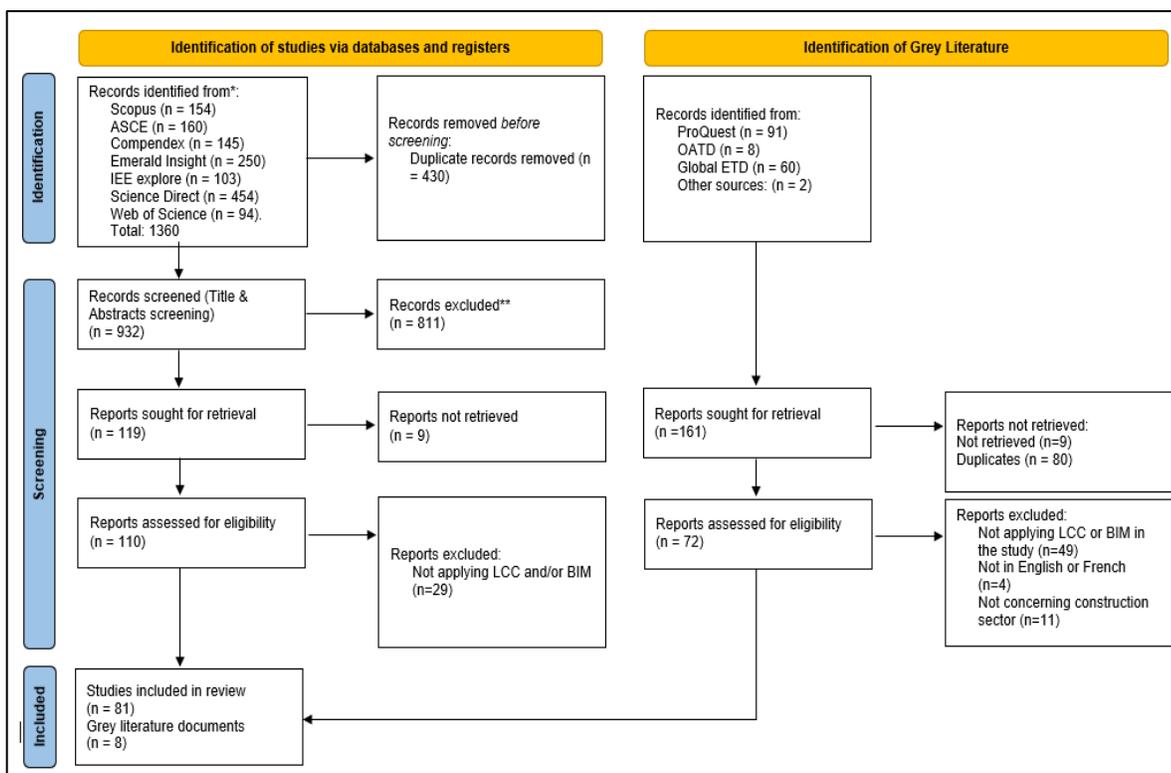


Figure A I. 1 PRISMA flow chart

The SLR was complemented with a conceptual analysis, as proposed by Jabareen (2009), to build a conceptual framework. Jabareen’s methodology involves steps resembling the data collection process of the SLR, but it goes further with subsequent steps that identify and name each concept found in the studies, to define them, their attributes and their role and integrate them into a conceptual framework.

4. Findings and Discussion

In this section the results of the data analysis are presented. First, the interactions between BIM and WLC are investigated to determine their complementarities. Then, the concepts resulting from the use of BIM and WLC will be identified and deconstructed before being integrated into a reference framework.

4.1. Complementarities between BIM and WLC

The results of the interaction between BIM and WLC when used in a project are summarized in Tableau A I. 1. The primary benefit of BIM is its potential to overcome the data accessibility barrier of WLC, that leads to time consuming quantification and cost estimation. In fact, BIM models have the potential to automate the approach thanks to their quantity take off (QTO) process and ability to integrate/be linked to a database. Some authors have worked on this, like Kehily (2017), who demonstrated how the 5D BIM tool CostX, can be used to extract quantity to conduct LCC estimation, or Santos (2020), who proposed to integrate LCC information directly inside the BIM model to automate the process. Moreover, easy simulation testing with BIM makes it possible to simulate alternative scenarios and see how WLC will affect the project. An example can be found in a study by Omaran (2019) in which he linked a game engine to BIM, to visit the project virtually and make changes to it, to highlight the impacts of the alternatives on the project LCC. BIM also helps in conducting WLC for organizational aspects, as it facilitates collaboration and the managing of the huge amounts of data needed to conduct an WLC analysis (Krigsvoll 2007). In his study, Rodrigues (2018) integrated shared parameters about maintenance, quantity, and costs into the BIM model to facilitate data management and prepare preventive maintenance plans. He supported his model with LCC to find best alternatives. Also, BIM reduces human errors and facilitates the use of WLC at early design stages for a more efficient approach application. Lee (2020) used a BIM-based LCC preliminary estimation at an early design stage and showed that BIM provided more precise results even at the design stage. Finally, WLC can provide a new indicator, which, once integrated into a BIM model, is easily readable and shareable (Di Biccari *et al.* 2019), reinforcing the decision-making process as it makes it possible to compare data on a financial basis.

Tableau A I. 1. Complementarities between BIM and WLC

WLC advantages for a BIM project	BIM advantages for a WLC approach
Reinforces decision-making and project cost control Enriches BIM model Reinforces life cycle thinking	Provides automatic quantity take-off Can serve as a repository database Easy simulation Facilitates management of data Facilitates the use of WLC at early design stage Provides better quality data and reduces human errors, increases precision Provides easily readable and shareable results

4.2. Synergic use of BIM and WLC

BIM greatly supports and enhances WLC. Conversely, BIM can be improved and augmented through WLC. The combination of both can make it possible to apply interesting concepts that can enhance a project financial control. Based on the analysis of the data collected, it appears that the combination of BIM and WLC can contribute to the application of processes, concepts and methodologies. The latter are summarized in Tableau A I. 2 and the next section will present how BIM and WLC facilitate their use. The process that is reinforced by the combination of BIM and WLC is decision making. This is the predominant topic in our research because supporting decision making is the purpose of WLC. Each study collected could have been identified in the DM line in Tableau-A I- 1, but only studies that focused on WLC are indicated for organizational purposes.

Concerning these concepts, a study from Di Biccari (2019) investigated the use of BIM to support Circular Economy (CE) and LCC indicators to compare alternatives more easily, while Kim (2020) proposed a design support tool for material reuse assessment, utilizing

BIM to extract data from the deconstructed structure and LCC as an indicator of assessment. Another concept found was Net Zero Emission (NZE), referring to energy consumption and carbon reduction. Some studies worked on both and some on just one. Akbarnezhad (2014) worked on both topics and evaluated disassembly techniques to find those best in terms of costs, energy consumption and carbon emissions. Of those who worked on just one of these topics, there is Kabassi (2012), who used BIM to build an energy model and LCC model to compare sustainable design to assess the cost-effectiveness of a Zero Net Energy Test House, and Figl (2019) who proposed a 6D BIM terminal to analyze projects through LCC and LCA to plan CO₂-neutral buildings. Energy and carbon were grouped because of the correlation between them. Another concept is value engineering, which merges the concepts of Value for money (VFM), value engineering (VE) and value management (VM). Jausovec (2019) used LCC to conduct a VFM analysis and find cost-effective prefabricated systems for a building, using BIM as a data repository and evaluation tool for LCC. Usman (2018) used the functionality of a 3D BIM model to facilitate the VE approach integrated with LCC. Punnyasoma (2019) used BIM for QTO and cost evaluation, and LCC to find the highest cost-effective solution with lowest LCC for VM. The final concept found was construction and demolition waste management (CDWM) studied by Zoghi (2020), reducing CDW costs using a BIM-based waste management system, and evaluating LCC effective solutions.

Regarding methodologies, Life Cycle Analysis (LCA) is a noticeable trend of study in the literature. In fact, LCA is presented as a complement to LCC and authors like Santos (2019) proposed a BIM-LCA-LCC framework by integrating parametric data into a BIM model. BIM-based WLC is also used to leverage Life cycle management (LCM). LCM regroups studies on whole life management as seen in the study by Rodrigues (2018) presented above, and studies on facility management as seen in a study by Vitiello (2019), who used BIM as a database and LCC as an indicator to evaluate the cost effectiveness of retrofitting designs, considering economic loss expectations in a context of seismic risk. Still, in life cycle thinking, the following two approaches are similar: Life Cycle Sustainability Analysis (LCSA) and Triple Bottom Line (TBL). Both use LCC as an indicator and measure environmental and social factors in specific metrics to complete their analysis. Figueiredo

(2021) used LCSA to select materials, partly using LCC in the evaluation and BIM as a database to extract quantities and simulations. An example of TBL is presented in the study by Phillips (2020), who used it to find the best window-to-wall ratio by conducting BIM-based LCA and LCC and measuring occupant satisfaction. Finally, Multi Objective Optimization (MOO) is another prevalent methodology in the literature. Sandberg (2019) proposed an optimization model based on a master model, which can generate different domain models for evaluation and optimization, then the optimal solution is sent back to the master model. He used an energy model and life cycle costing model to find the optimal sustainable performance for a building.

Tableau A I. 2 Identified concepts from the application of BIM and WLC

Process		
Decision making (DM)	Process of choosing options and alternatives according to project expectations. Its main objective is to optimize the investments made to obtain expected performance.	(Bernard 2007, Krigsvoll 2007, Sullivan and Horwitz-Bennett 2009, Szönyi 2010, Marzouk et al. 2013, Jalaei et al. 2015, Dawood 2016, Kehily 2016, Ahmadian F.F. et al. 2017, Alsayyar and Jrade 2017, Juan and Hsing 2017, Kehily and Underwood 2017, Omaran et al. 2019, Saridaki et al. 2019, Whyte and Scott 2019, Zanni et al. 2019, 2021, Altaf et al. 2020, Gao et al. 2020, Kalemi et al. 2020, Lee et al. 2020, Bernardino-Galeana et al. 2021, Bianchi et al. 2021, Piaskowski and Svidt 2021, Rad et al. 2021)

Tableau A I. 2 Identified concepts from the application of BIM and WLC (suite)

Concepts		
Circular Economy (CE)	Concept that has a closed-loop life cycle perspective of products instead of a linear life cycle perspective by utilizing restorative/regenerative designs. It is used to optimize the use of products/ materials to reduce waste generation.	(Akbarnezhad et al. 2014, Di Biccari et al. 2019, Kim and Kim 2020)
Net Zero Emissions (NZE)	Concept used for the design of high energy efficiency buildings to reduce energy consumption and thus carbon emissions, to reduce the building's carbon footprint.	(Kabassi and Cho 2012, Loh et al. 2012, Liu et al. 2015, Nour et al. 2015, Oti and Tizani 2015, Sleiman et al. 2017, Figl et al. 2019, Rashed et al. 2019, AlizadehKharazi et al. 2020, Hassanizadeh and Noorzai 2020, Kaewunruen et al. 2020, Odeh 2020, Pučko et al. 2020, Zhuang et al. 2021)
Value Engineering (VE)	Concept used to optimize decision making to create value through the life cycle of a project by considering costs, benefits and quality.	(Kim and Park 2018, Usman et al. 2018, Jausovec and Sitar 2019, Punnyasoma et al. 2019, Yuan et al. 2020, Khodabakhshian and Toosi 2021, Sathe and Pimplikar 2021)
Waste management (WM)	Concept relating to the optimization and reduction of construction waste production, reuse, recycling and disposal.	(Akbarnezhad et al. 2014, Zoghi and Kim 2020)

Tableau A I. 2 Identified concepts from the application of BIM and WLC (suite)

Methodologies		
Life cycle analysis (LCA)	Cradle-to-grave analysis to assess and quantify the environmental performance of a product or project. Used to collect and analyze environmental data to assess impacts.	(Dawood et al. 2009, Shin and Cho 2015, Bruce-Hyrkas et al. 2018, Raposo et al. 2019, Santos et al. 2019, Ansah et al. 2020, Barbini et al. 2020, Santos, Costa, Silvestre, and Pyl 2020, Santos, Costa, Silvestre, Vandenberg, et al. 2020, Carvalho et al. 2021, Lu et al. 2021)
Building Life cycle management (BLCM)	Data asset manipulation and exchange throughout a building's life cycle. It helps to manage the asset's performance throughout its life cycle and guarantee its serviceability.	(Zheng and Cao 2013, Rodrigues et al. 2018, Chen and Tang 2019, Vittello et al. 2019, Matos et al. 2021, Vadapalli 2021)
Life cycle sustainability assessment (LCSA) and Triple Bottom Line (TBL)	MOO approaches based on the three pillars of sustainability (social, environmental, and economic) to optimize projects. Their objective is to analyze the durability of an asset through its environmental, economic and social performances.	(Karunasena and Rajagaloda Gamage 2017, Llatas et al. 2020, Phillips et al. 2020, Figueiredo et al. 2021)
Multi-Objective Optimization (MOO)	Methodology that aims to obtain the best trade-off between two or more expectations for a design or project. Its role is to analyze a product/project on multiple planes to highlight its specific performances.	(Cheung et al. 2012, Loh et al. 2012, Dawood 2016, Marzouk et al. 2016, 2018, Eslam Mohammed Abdelkader and Marzouk 2017, Moghtadernejad et al. 2019, Sandberg et al. 2019, Abbasi and Noorzai 2021, Sharif et al. 2021, Zhang et al. 2021)

Additionally, Tableau A I. 3 presents Machine Learning (ML) and Genetic algorithm (GA). Both are emerging as a new trend to enhance WLC. Gao (2020) proposed a ML-based framework to analyze the LCC of facilities. The framework uses a BIM model and design and construction documentation to collect descriptive data for the ML models with different methods of calculation. Then an evaluation phase provides the method and results for the project. Dawood (2016) used a GA to combine multiple variable components and found the combination that best represents the optimal LCC of the project. He used a BIM model to serve as a database for the building components, find the quantities for initial cost estimation and perform an energy analysis.

Tableau A I. 3 WLC facilitators

Facilitators		
Machine Learning (ML)	Develops predictions through the automatic evaluation of a set of data patterns	(XH Gao, Pishdad-Bozorgi, Shelden, & Tang, 2020 ; Sharif, Hammad, & Eshraghi, 2021)
Genetic Algorithm (GA)	Optimization method based on the human chromosome model. Each chromosome represents a solution composed of several genes representing components of the solution.	(Dawood, 2016 ; M Marzouk, Azab, & Metawie, 2018 ; M. Marzouk, Hisham, Elsheikh, & Al-Gahtani, 2013 ; Nour, Hosny, & Elhakeem, 2015 ; Sandberg, Mukkavaara, Shadram, & Olofsson, 2019)

5. Reference framework creation

Concepts previously defined are now integrated into the reference framework presented in Figure A I. 2. The framework establishes the links between the combination of BIM and WLC, the different process, concepts, methodologies and facilitators. The BIM/WLC

combination and in particular the application of WLC, can be facilitated by ML and GA. Then, WLC can leverage the methodologies identified, which can in turn help to implement the concepts of CE, NZE, VE and WM. Finally, the decision-making process is the basis of the hierarchical organization of the framework, as it is the underlying purpose of each of these elements. For the methodologies, WLC provides a financial perspective when assessing assets and BIM can serve as a data repository, facilitate data management and extraction and can be used to perform simulations. As for the concepts, WLC is used as an indicator for representations, facilitated through BIM.

By comparing the WLC barriers described in the literature review and BIM-WLC complementarities and synergies, it appears that, considering an optimal combination of the two, major barriers of WLC could be overcome. Indeed, BIM can reduce the time and complexity of the process of WLC considerably and even automate it. It can help to manage data and encourage information sharing to conduct the estimation. One of the major opportunities that BIM can offer is its ability to store data and act as a database, satisfying the need for complete and easily accessible life cycle data. Easy simulation of BIM can help to generate alternatives and increase the precision of WLC results. In addition, the synergic use of BIM and WLC offers the opportunity to apply other concepts that could be more adequate and efficient or complementary to WLC, depending on the project. Unfortunately, the application of an optimal BIM-based WLC approach is still faced with certain barriers. Indeed, there is still a lack of standardization in its methodology, data gathering remains a challenge and interoperability issues may prevent the use of BIM (Zanni *et al.* 2021). In addition, there are barriers to WLC that BIM cannot yet overcome. Indeed, the concept of the approach is still complex despite BIM and it is recommended that the non-informed project stakeholders receive training (*L'union sociale pour l'habitat 2018*). Also, confidence in WLC predictions still depends on the reliability of forecasting and the right choice of discount rate. In fact, even if BIM overcame some barriers, a great subjectivity would remain as to the choice of parameters, meaning that errors in forecasting could still occur and falsify the results.

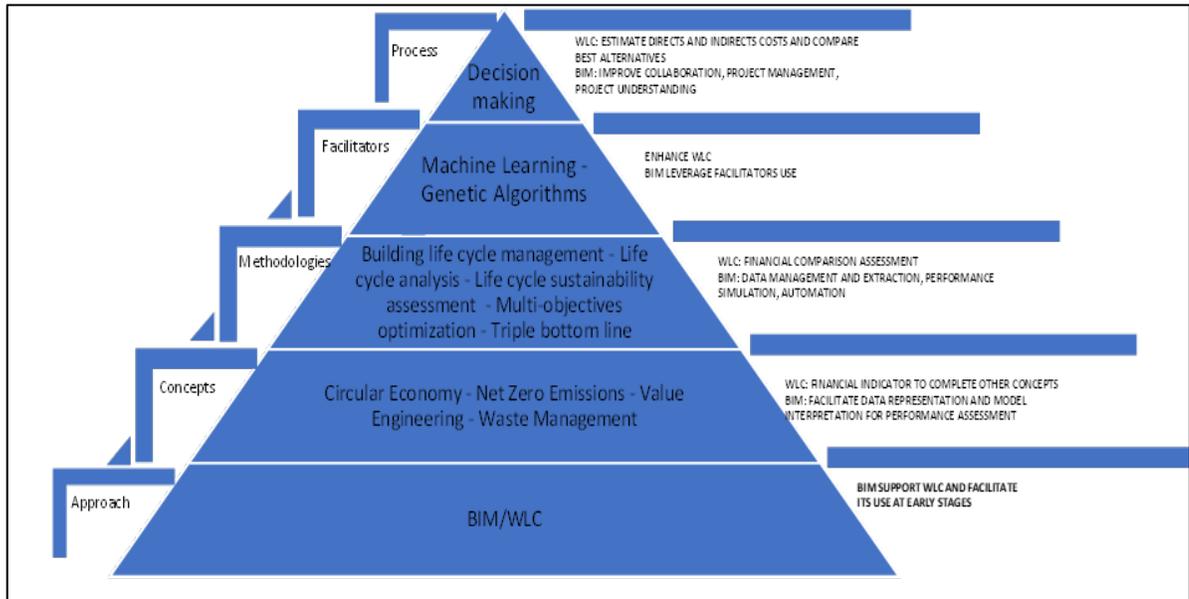


Figure A I. 2 Frame of reference for the use of BIM-WLC combination

6. Conclusions and Further Research

WLC is an appropriate method to assess investments that are beyond the initial costs of a project. The approach can be useful to control the direct and indirect costs of a project and produce value. A recent trend in the literature is to use both BIM and WLC to improve the cost estimation approach. The present research aimed to explore the synergies between BIM and WLC through a systematic literature review. It was found that BIM and WLC are complementary. BIM helps to overcome some of the barriers of WLC and WLC supports the life cycle thinking and collaborative nature of BIM. Moreover, their synergy makes it possible to use other concepts like circular economy or value engineering. The combination of BIM and WLC has a great potential to improve practices in the construction industry. The present paper also showed that BIM and WLC have a great potential to improve decision making in projects. Many studies also showed the benefits of WLC when leveraging it with environmentally-friendly and/or value producing concepts. Furthermore, current literature seems to be directed towards technological improvements such as interoperability, which is one of the main obstacles of BIM. More recently, the literature has mostly tended to optimize the BIM-WLC combination to fully take advantage of it, by leveraging facilitators like

machine learning and genetic algorithms to enhance WLC results, and some authors relied on databases to fully overcome the data gathering barrier(M. Altaf et al., 2020)(M. Altaf et al., 2020)(Altaf et al., 2020). Further study should address the fundamental issue of the confidence in predictions by WLC and its parameters, because these are the principal reasons why long-term budgeting is not in the habit of owners and why the widespread adoption of WLC is hindered. Finally, further studies should explore the application of BIM and WLC at different project scales and identify the context in which the combination of BIM and WLC is most beneficial. Concerning this work, more grey literature could and should be added to the study, but accessibility to grey literature is still a major barrier to its consideration. Industry actors generate a lot of quality data and it could be interesting to investigate a significant amount of it to collect feedback on this subject from their experiences.

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ANNEXE II

A CASE-STUDY INVESTIGATING THE INTEGRATION OF ISO 19650 AND OPENBIM PRINCIPLES

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Abstract

The digital transformation of the construction sector is leading to a wider adoption of project digitization, process automation, and new project methodologies, demonstrating numerous benefits for sector productivity. This growth is pushing the sector more than ever into the era of digitalization, along with the issues that come with it. Managing the large amount of data from multiple different sources, multiple tools and software, and multiple project stakeholders represents a challenge in terms of interoperability and collaboration in the construction sector. Building Information Modelling (BIM) as a collaborative process has been discussed for improving interaction and exchange between both software and people. Structuring this approach, ISO 19650 provides guidelines on how to manage project data efficiently, whereas BuildingSMART International promotes the use of the openBIM approach, based on IFC open data schema, and propose a set of tools and processes aiming to facilitate the exchange and integration of data for all project participants, regardless of their working discipline. The approaches supported through ISO 19650 and openBIM share similar purposes, aiming to improve project data management, exchange and flow. This

paper presents an integrated approach to the application of ISO19650 and openBIM principles to leverage the benefits from both standardized orientations. The study uses a Design Science Research methodology to implement the approach in a renovation project, to understand its foundations and issues. The paper provides an example of the ISO 19650 applications, supported by openBIM concepts to ensure interoperability. This study contributes to the ISO 19650 understanding and openBIM approach adoption in both academic and industry fields by testing its practicability and proposing an experimented process, but also by identifying strengths and weaknesses, as well as points of attention for leveraging the value of this approach.

Keywords: openBIM, ISO 19650, Information Management.

1. Introduction

The technological advances and the pursuit for more sustainable and efficient structures have pushed the Architecture Engineering Construction (AEC) industry into the era of digitalization. The greater amount of produced and available data, coupled with a concerted effort to increase productivity in construction procedures through enhanced collaboration presents a great challenge for the industry.(McKinsey & Company, 2020) This escalating challenge has propelled Building Information Modelling (BIM) into the spotlight as an increasingly prevalent solution. With its dedicated emphasis on data gathering and management, BIM has swiftly emerged as an indispensable tool, demonstrating not only relevance but also vast potential in addressing the industry's evolving needs.

However, the adoption of BIM is still in its infancy, slowly but surely integrating the construction industry's complex practices. Among the barriers to its acceptance, there is the lack of standardization, specifically in aligning its application across the entire life cycle of built asset. This is where the ISO 19650 series of standards intervenes, offering a framework that can be applied by professionals operating in diverse construction domains and varying levels of complexity. From the first stages of planning to the end-of-life of the construction

life cycle, the ISO 19650 series of standards has evolved into a foundational cornerstone, facilitating the seamless harmonization of BIM practices throughout the industry.

As the industry's knowledge of the BIM approach has grown, so too has the development of software aligned with this methodology. However, this progress has inadvertently led to a proliferation of file formats, turning what was meant to simplify information exchange and collaboration into a potential obstacle (Wierzbicki, de Silva, & Krug, 2011). The tools first designed to improve communication can introduce unintentional barriers to integration, creating a fragmented scenario between different systems and professionals.

While the ISO 19650 standards mark a step in the standardized use of BIM, they fall short in addressing the critical aspect of interoperability—an indispensable function for effective collaborative work- they refer instead to the BuildingSMART standards(Churcher, Davidson, & Kemp, s.d.). The BuildingSMART Association has championed openBIM as a solution for achieving interoperability(« openBIM Definition - buildingSMART International », 2020). Although the efforts of BuildingSMART in providing process and resources in openBIM are substantial, challenges remain as to how these align with data and information management practices. Considering the upcoming needs of the construction technology domain, the following problematic arise: How can AEC stakeholders leverage openBIM principles to support a structured approach to data and information management as defined in the ISO 19650 series of standards?

The adoption of open formats holds the promise of seamlessly tying various tools and systems together through a common data schema, expediting information sharing and fostering greater efficiency.

Despite the growing interest of the academic community regarding openBIM (Jiang, Jiang, Han, Wu, & Wang, 2019c), there is a lack of information about its practical application information in the existing literature. To bridge this gap, the authors of this article sought to design an artifact that offers guidelines for the effective use of these tools in conformity with

the ISO 19650, as well as identifying the benefits and barriers of its use. The artefact was developed and validated in a low-complexity project.

A range of various market-available tools were considered to develop this new tool. The strategy for the tool choice involved extracting the optimal capabilities from each tool to tailor solutions that precisely met the unique needs of their projects. This nuanced approach aimed not only at mitigating the challenges posed by interoperability but also at maximizing the potential for collaboration and efficiency in the AEC industry.

This article will unfold with a detailed literature review, wherein the authors will present the synergies found between openBIM and the ISO 19650. The study employed the Design Science Research methodology, a robust research framework used to address complex problems by creating artefacts capable of tackling real-world issues.

Finally, the results obtained will be presented and critically examined, shedding light on the strengths and weaknesses of the proposed framework. Based on the artefact test the authors can propose further research paths to be taken for advancing the openBIM adoption.

2. Literature review

Structured information management: the ISO 19650 series of standards

Information management is an important element in the construction sector and requires clear structuring. Standardization, digitization and the rationalization of information are issues to which ISO 19650 responds through a framework (« ISO 19650 Guidance 0: The case for information management », s.d.) for defining information requirements, planning the delivery of this information and the way in which it is delivered and approved (« ISO 19650 Guidance 1: Concepts », s.d.).

Standardizing the way in which information is managed ensures that it is of good quality, that it "can be appropriately exchanged, queried and re-used for different purposes across a range of technologies" (« ISO 19650 Guidance 0: The case for information management », s.d.).

According to Pan and al, following the recommendations of ISO 19650 simplifies information management. Indeed, the allocation of responsibilities is clear, and it offers "flexibility in the way requirements are met" (X. Pan et al., 2023). They also stress the importance of standards in establishing "best practice" and organizing the work of collaborative teams on an international scale.

Almeida and al. recognize the usefulness of information management standards in facilitating the implementation of new aspects of BIM, particularly environmental information.

There are many advantages to implement this standard in projects, such as better management of the various stages of the project (planning, construction, operation) or support for more sustainable use of a built asset over its entire lifespan (« ISO 19650 Guidance 4: Information exchange », s.d.).

However, although the benefits are numerous, they are sometimes difficult to quantify. ISO 19650 Guidance 0 contains reports on quantifying these benefits. The Met Office, for example, has forecast a cost saving of around 18% for the design and procurement phases of its new facilities. In Scotland, the Environment Agency reported a saving of over £1 million on the resources required to provide "access to asset data during the project handover" (« ISO 19650 Guidance 0: The case for information management », s.d.).

Despite the structured framework offered by ISO19650, recurring problems persist around interoperability of information systems used throughout built asset lifecycles.

2.1. Improving interoperability: openBIM

The significant amount of information generated by a project and coming from different design tools leads to numerous challenges related to data exchange (Khudhair, Li, & Ren, 2023). The issue of interoperability is described as the ability of several "heterogeneous computer systems to function jointly, through the use of common languages and protocols, and to provide reciprocal access to their resources" (« Thésaurus de l'activité gouvernementale », s.d.).

Turk (Turk, 2020) presents three levels of interoperability: (1) person-person: collaboration (social and communication), (2) person-system: communication between systems via the use of tools and technologies; (3) person-semantic: "common and unambiguous understanding of the information exchanged" (« Thésaurus de l'activité gouvernementale », s.d.).

In order to respond to these different levels of interoperability, BuildingSMART has promoted the concept of openBIM, a process based on transparent collaboration supported by the unhindered flow of information across project networks (« buildingSMART International », s.d.). BuildingSMART is an international not-for-profit organization (NPO) that seeks to develop open standards to support the industry in information management. The various concepts that make up openBIM aim to "maximize data interoperability" (Shehzad et al., 2021).

2.2. The concepts behind openBIM

Several standards constitute the openBIM concept. These standards present different objectives and implementation challenges, as shown in the below.

Tableau A II. 1 openBIM concepts

Concepts	Definition	Benefits	Challenges	References
UCM	Use case Management; grouping of BIM use cases spread throughout the project value chain, which are the BIM objectives.	Clearly define the use case with its objectives, scope and limit	Not all BIM use cases have yet been referenced.	(« Use Case Management Use Case Management », s.d.)
IFC	Industry Foundation Classes; data schema used to represent, store and share data.	Data schema that can be understood by different types of software.	The IFC schema structure is complex.	(« buildingSMART International », s.d.), (Jönsson, 2015)
bSDD	BuildingSMART Data Dictionary; online dictionary that hosts concepts, defines them, shares them and connects them to other standards or elements outside the IFC.	Implementation of a common language that can be understood by all software.	Requires the use of an API, of which there are not many for this concept.	(Churcher et al., s.d.), (« ISO 12006-3:2022), (« ISO 23386:2020, Modélisation des informations de la construction et autres processus numériques utilisés en construction — Méthodologie de description, de création et de gestion des propriétés dans les dictionnaires de données interconnectés », s.d.), (Jiang et al., 2019c), (Navathe & Kerschberg, 1986)
IDM	Information Delivery Manual; a document containing at least one-use case, a process map and information requirements.	IDM is the basis for the development of MVDs.	Creating IDMs is a tedious and technical process.	(« ISO 29481-3:2022, Modèles des informations de la construction — Protocole d'échange d'informations — Partie 3: Schéma de données », s.d.), (Churcher et al., s.d.), (Khudhair et al., 2023), (Arayici, Fernando, Munoz, & Bassanino, 2018), (« BIM basic Information Delivery Manual », s.d.)
Open file format	Non-proprietary file format.	Can be used or modified by anyone.		(« buildingSMART International », s.d.)

Tableau A II.1 openBIM concepts (suite)

IDS	Information Delivery Specification; document grouping together the information requirements for the assets in the model.	Facilitates the development of requirements and enables the enrichment of model assets to be verified.	Specific software is required to create them.	(« buildingSMART International », s.d.), (van Berlo, Willems, & Pauwels, 2019)
BCF	Bim Collaboration Format; Collaboration and communication format.	Improves and facilitates communication around a model.	Requires the use of an API.	(« buildingSMART International », s.d.)

2.3. The BuildingSMART proposed integrated openBIM workflow

BSI have presented a series of best practices to support practitioners in the application of their concepts. Among those, they proposed a process to create project data in an open format and respecting project requirements (see Figure A II. 1). The process starts with the creation of an IDS, defining data requirements thanks to UCM. Next, the IDS is sent to the modeller who choose the right software to create the required data. Then the modeller could then enrich the model based on IDS requirements and also using the bSDD. After the enrichment, the modeller verifies the data contained in the IFC file thanks to the IDS, enriching the model if data is missing or incorrect and exporting the validation errors report in the form of BCF comments attached to the file. The validated version of the model is then exported to IFC format to send it to the client who will be able to validate the file with the IDS.

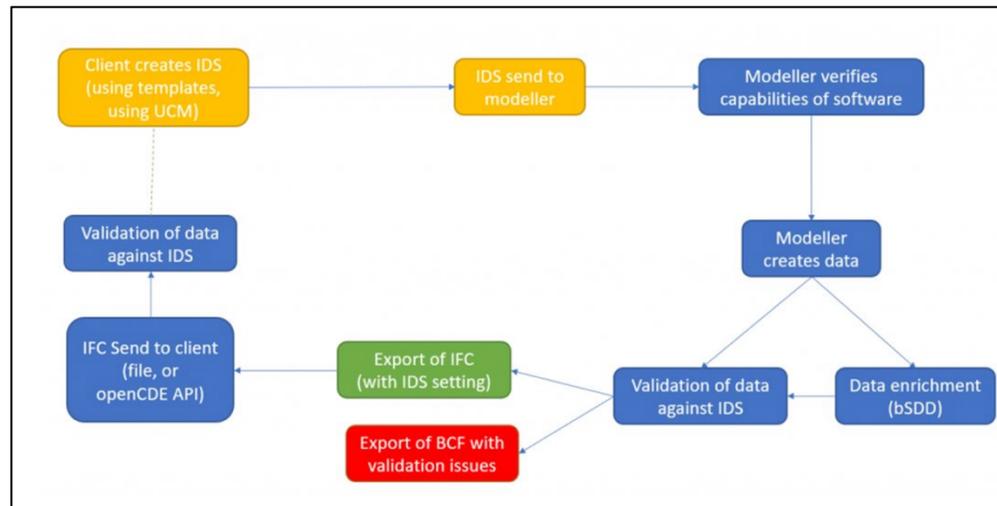


Figure A II. 1 openBIM workflow

From (Van Berlo, 2022)

ISO 19650 suggests working with open data to ensure project interoperability. OpenBIM is therefore named by the UK BIM Framework as a compelling solution. However, few studies tried to leverage an openBIM-ISO19650 alliance and solutions to implement it. Pan and al. (X. Pan et al., 2023) deals with the use of ISO and openBIM, but at the scale of the implementation of a country (Pakistan) and therefore does not recommend any real practical application. Another study proposed by (Almeida, Chaves, Silva, Carvalho, & Caldas, 2023) introduces the integration of Environmental Product Declarations (EPD) into projects, using ISO 19650 to facilitate the definition of the requirements involved by EPDs. The openBIM approach is implicitly used using IFC and the concept of IDM to enable the efficient feeding of data to EPD sheets. However, this study lacks the use of the full concepts of openBIM as presented by BuildingSMART. McGinley and al. (McGinley et al., 2023) tried to carry out this approach in the context of working with students and proposed an ISO-openBIM framework despite the lack of time to test it. Literature presents a lack of application of an ISO 19650 approach with openBIM concepts that needs to be filled as a priority to have experiences and be able to come up with an approach that is consistent with today's challenges. This paper aims to contribute to filling this gap by describing the application of an openBIM-ISO19650 process used in a study project.

3. Research methodology

This project is the result of a student initiative within the Research Groupe for Integration and Sustainable Design in the Built Environment (GRIDD). Five master's students and one doctoral student were given the opportunity to practise industry standards by simulating real project conditions. This gave the students the opportunity to put their acquired knowledge and skills into practice in a multidisciplinary context. The renovation of a duplex in Montreal was chosen as the case study. The aim of the research is to develop and test an approach which integrates openBIM principles into the ISO 19650 framework. To achieve this objective, a Design Science Research (DSR) project was undertaken and is supported by a real project case allowing creating practical knowledge. DSR consists in the production of an artifact aiming to solve an identified practical problem, this based on defined theoretical foundations. (Dresch, Lacerda, & Antunes Jr, 2015b). This method revolves around 3 cycles as presented by Hevner, (A. R. Hevner, 2007b), namely: the relevance cycle, the rigor cycle, and the design cycle which is central to the research (see Figure A II. 2):

- Relevance cycle: the aim of the relevance cycle is to ensure the artifact produced contribute to improve the application domain (A. R. Hevner, 2007b). The relevance cycle leads to requirements definition and the evaluation of the artefact with a field-testing considering acceptance criteria (A. R. Hevner, 2007b). In this study, the application domain is information management, requiring an improvement of the ISO19650 process thanks to openBIM approach. The field-testing corresponds to the use cases application.
- Rigor cycle : the rigor cycle aims to ensure the artefact contribute to an innovation, basing itself on and improving the knowledge base, i.e., state of the art in the domain and existing artefacts and processes (A. R. Hevner, 2007b). In this study, our knowledge base is mostly composed of existing processes and practices of ISO 19650 and openBIM, and the literature around them.
- Design cycle: finally, the design cycle, being the central element of the methodology, aims to iteratively build the artefact, swinging in balance between the other cycles (A. R. Hevner, 2007b).

The steps of the design science methodology as presented by Dresch (Dresch et al., 2015b), have been adapted in this research. The steps followed are:

- Step 1: Problem Identification
- Step 2: Awareness of the problem via the literature review
- Step 3: Proposition of an artifact
- Step 4: Design of the artifact
- Step 5: Application and Evaluation of the artifact
- Step 6: Clarification of learning achieved & Conclusions.

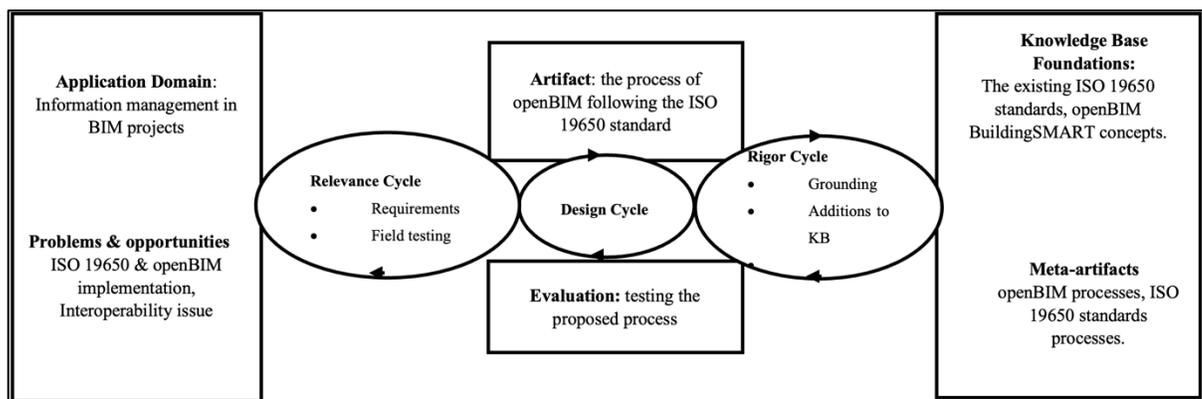


Figure A II. 2 Project's research framework based on Design Science Research

Adapted from (A. R. Hevner, 2007b)

Artifact validation was carried out in the three steps proposed by Larsen (K. Larsen et al., 2020). The first stage is an Ex-Ante evaluation, which will ensure that theoretical congruence is assessed. Theoretical congruence corresponds to the consistency of the standards chosen for the problems addressed in this study. The second step is an assessment of the artifact's development cycle, ensuring its internal validity and input data. Internal validity corresponds to the artifact's consistency with the initial functions of the standards. Input data here corresponds to the tools used to make the framework functional, i.e., compatible with open data. The final stage is an Ex-Poste evaluation of the rigor cycle, ensuring that the knowledge domain is enhanced by a new framework combining the two standards and its application in this project simulating a real project.

4. Results

4.1. Artefact proposition

The resulting artifact of the project is a process combining the ISO 19650 and the different openBIM concepts (see Figure A II. 3).

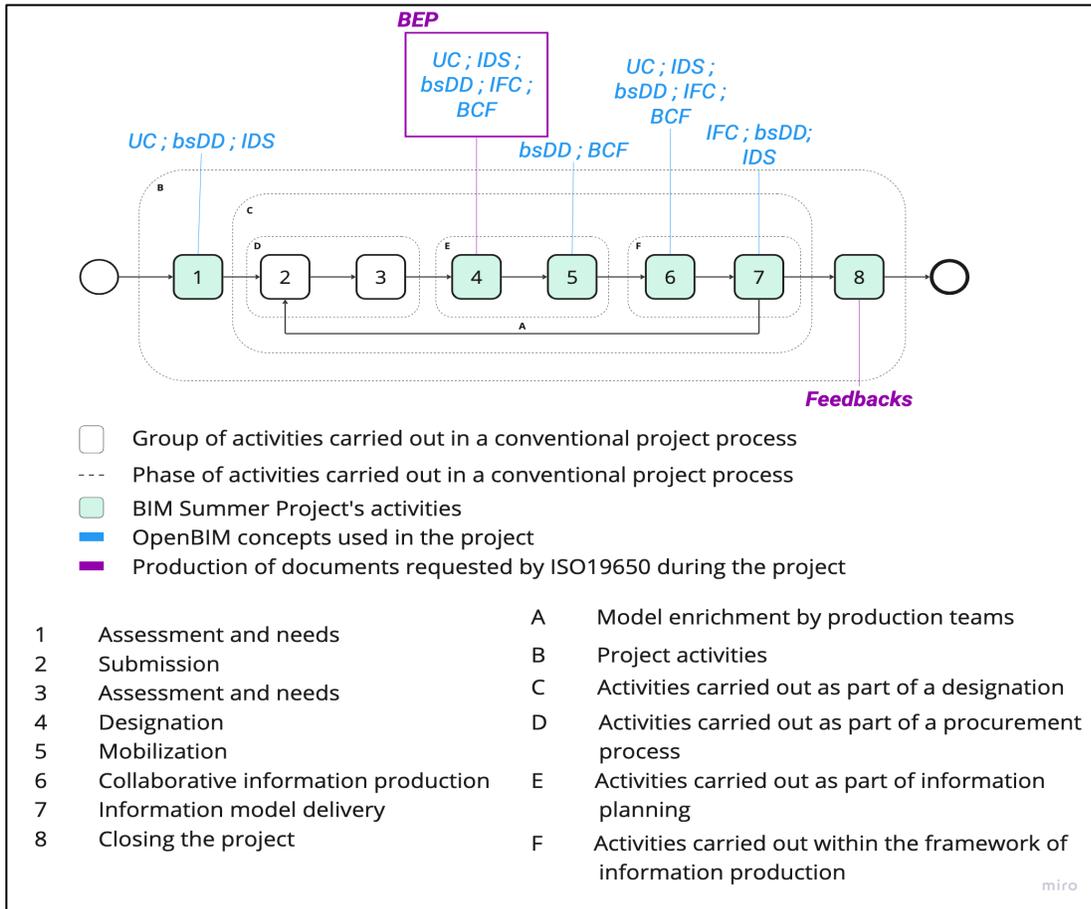


Figure A II. 3 ISO 19650 process integrating openBIM concepts

The process for this project excludes the phases 2 and 3 which are outside of the project scope, as it concerns procurement process. The process is thus composed of the following phases:

- 1- Assessment and needs: The first phase starts with the team definition and aims to define the tasks requirements of the project. In terms of the ISO, it means developing OIR, PIR, AIR and EIR.

At a strategic level, meaning at the client's portfolio or asset level, Organization Information Requirements (OIR), as defined in ISO19650 Guidance D, is the information required by the asset's owner to achieve the organization's objectives. Those OIR aims at guarantee that the needs are met for the proper conduct of activities planned for the assets.

Next, the asset's owner needs to identify the information required per assets according to its priorities. From OIR, Asset Information Requirements (AIR) will be developed for a specific asset or a group of assets.

The project owner also defines Project Information Requirements (PIR), that is the information required to achieve the project strategic objectives. In line with the OIR, PIR aims at guide decision-making during the design and construction phases. The PIR needs to describe information for a specific scope and the purpose for which the information is to be used. It also needs to consider the project planning, the contractual mode, required decisions and the milestones for progressing the project.

From the PIR and AIR, Exchange Information Requirements (EIR) are defined. EIRs describe the information that needs to be processed in order to achieve the PIR and AIR. For each of them, EIR needs to set the information receiver and provider, the information delivery milestones, the type of the deliverable and its format. EIR from AIR will define operational requirements and EIR from PIR will define delivery requirements.

To add the openBIM concepts, use cases (UC) are defined according to OIR and PIR. IDS are developed based on AIR and EIR (Figure 5). bSDD terms are used to write the asset information requirements contained inside the IDS. The goal with the use of bSDD is to use a common language.

- 2- *Submissions: Not covered in this project.*
- 3- *Assessment and needs: Not covered in this project.*
- 4- Designation: This phase concerns the BIM execution plan redaction (based on ISO 19650, and the Annexe Canadienne (2018) for this project), which describes the work standards to be respected. To implement the openBIM concept, UC were added as a part of the BEP, and IDS, bSDD, IFC and BCF were indicated as requirements to validate the project processes.
- 5- Mobilization: In the mobilization phase, the project technological infrastructure is set. This phase suggests that the team organize the project process around available resources. In this project, a CDE and different tools for UC realization have been determined. Tools were selected considering their usability with the openBIM approach, i.e., IFC representation, storage and sharing, bSDD common language and connection, BCF available for communication.
- 6- Collaborative information production: This phase is the execution of the different UC, following the processes defined and based on the requirements (EIR and AIR). The outcomes of this work are Project Information Models (PIM), that are information models for the delivery phase. PIM are produced and checked to ensure they are ready for the construction phase. If there was something was not compliant, BCF was used to inform of errors about PIM.
- 7- Information Model Delivery: To be sure that the client will be able to operate its asset efficiently, a verification of the PIM from the previous phase is realized. Once the PIM is validated it could be integrated into the Asset Information Model (AIM), that is information model for the operation phase.
- 8- Closing the project: This final phase concerns the provision of feedback and reporting the project.

4.2. Artefact application

A renovation project of a duplex in Montreal, Canada, was chosen to test the ISO19650 - openBIM approach. The applied approach consisted of seven stages: project definition, project planning, BIM Execution Plan, modelling, coordination, cost estimation analysis and

reporting. Each stage is related to the ISO 19650 process guidelines (see Figure A II. 4). The project is described in detailed below.

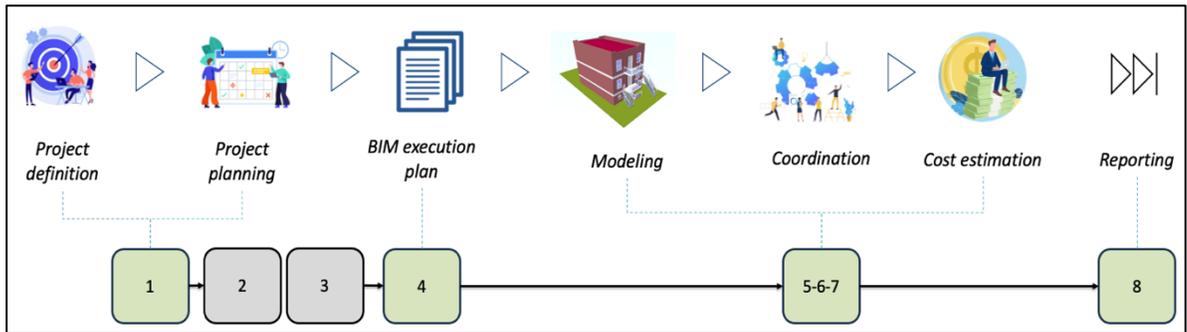


Figure A II. 4 Applied approach, in conformity with ISO 19650 guidelines

Project definition and Project Planning

Assessment and needs. Accordingly, to the defined process, the BIM team, has been defined. In the context of this study, the research team oversaw the information management and voluntary students were chosen to perform tasks needed for the project. To simulate a real situation, the team's role was defined as BIM consultants to support an architect in charge of renovating the asset. The next ISO step is to define all the information management requirements (see Figure A II. 5), i.e., OIR, AIR, PIR and EIR. Once those requirements are defined, the IDS could be developed. It will allow verification of the IFC files from PIM and AIM.

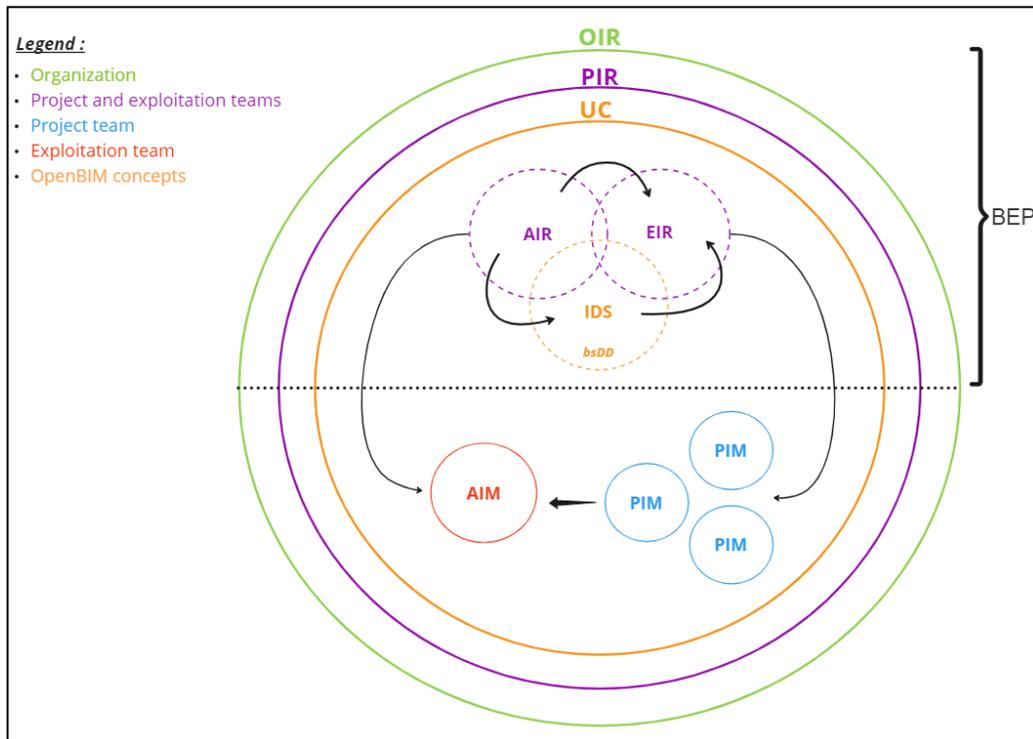


Figure A II. 5 Information management requirements definition process

In the context of the student's project, Architect's needs are: to better understand the existing structure to propose a coherent renovation option, to exploit the BIM coordination capabilities for the realization of the project, and to propose a cost-effective and high-quality design. Considering these needs, requirements have been defined:

- OIR definition: From a strategic point of view, the architect must propose to its client a cost-effective design. Then the OIR are generating a design that meets the needs of the architect's client and reducing construction costs as much as possible. For the project purpose, we also define the need of the architect for good data management in its projects. A third OIR is then to standardize and facilitate the data management practices.
- PIR definition: The PIR must reflect operational objectives in design and construction. Considering the OIR, PIR are defined as leveraging ISO 19650 – openBIM process

into the project, leveraging BIM capabilities to support design activities and cost simulations based on design options.

- Use cases definition: Following these requirements, the openBIM approach can be integrated at this time by defining Use Cases corresponding to the OIR and PIR aims. UC were defined as explicated by the BuildingSMART's UCM concept. The projects UC are: Existing conditions modelling (« BIM Uses | BIM Planning », s.d.), New designs modelling (« BIM Dictionary », s.d.), Code checking & validation (« BIM Dictionary », s.d.), Design coordination (« BIM Uses | BIM Planning », s.d.), Model-based quantity take-off (QTO) (« BIM Dictionary », s.d.) and Cost Calculation (« BIM Uses | BIM Planning », s.d.).

- AIR definition: For the AIR, each UC were attributed to the whole or a part of the asset. Modelling, QTO and estimation were attributed to the whole building. The Code checking & validation part concerned the verification of the whole model and specific rules are added for wall elements. Then the information needed to be extracted from these elements in the digital model has been defined. AIR are: Digital model of the existing and new building design needs to be available, shared and interoperable at all times. All elements modelled must be classified in a standardized classification. For the Code checking & validation, wall elements must comply with check the following rules: walls should have a Name; be Loadbearing; respect a range for AcousticRating and FireRating ; have a Material that belongs to the predefined list. Those rules have been converted into an IDS, backed by the bSDD. The example of the IDS for a wall requirements verification is shown in (see Figure A II. 6).

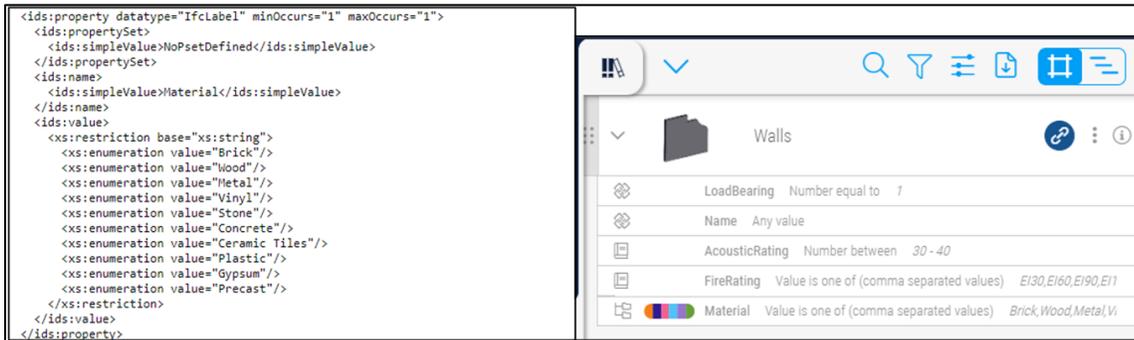


Figure A II. 6 IDS presented in XML form (left) and from Plannerly (right)

- EIR definition: Each UC have been detailed in terms of objectives, timing of realization (milestones), information needed and outputs and files format exchange. Meanwhile, a high-level responsibility matrix for each UC has been defined and integrated in the BEP. To ensure collaboration and communication, and as suggested by the standard, a Common Data Environment (CDE) will be set to centralize the communications, and this CDE should also be compatible with IFC and able to leverage BCF. Detailed EIR are presented in the Tableau A II. 2.

Tableau A II. 2 Project Exchange Information Requirements

UC	EIR	Form	Format	Information Exchange Date	Plain language description	Comments
Modelling (existing conditions and new designs)	Generating a digital model of existing and new building design in an open format	3D model	.rvt / .IFC (Revit)	Milestone 1	Architectural 3D model	Modelling existing building and new design proposal
Code checking & validation	A model coordination for model quality check for the specific rules of the wall elements	Report Rules Code	.pdf / .xml (Plannerly)	Milestone 3	Elements validation	Applied for walls. Rules: -have a Name be Loadbearing -respect a range for AcousticRating - respect arange for FireRating -have a Material that belongs to the predefined list
Model based QTO	QTO of elements of deconstructed and added between the existing and new building design	Work Breakdown Structure	.xlsx (Excel)	Milestone 3	Work Breakdown Structure	Quantities differences between existing and new building design
Cost estimation	A budget estimation for renovation works	Cost Breakdown Structure	.xlsx (Excel)	Milestone 4	Budget estimation	Cost of new design proposal

Finally, the first phase of assessment and needs also concern the planning of the project. Thus, a pull planning technique was employed based on the BIM uses and the EIR'S milestones.

4.3. BIM Execution Plan

Designation. The BEP has been formalized thanks to the Canadian Annex to ISO 19650-2:2018 (2018), giving guidelines for its completion and using Plannerly's platform, providing

comprehensive templates aligned with the ISO 19650 standard (see Figure A II. 7). The BEP contained the following parts: Project information, BIM teams and roles, Uses Cases, Project Processes, Project Standards, LOD Matrix, Resources.

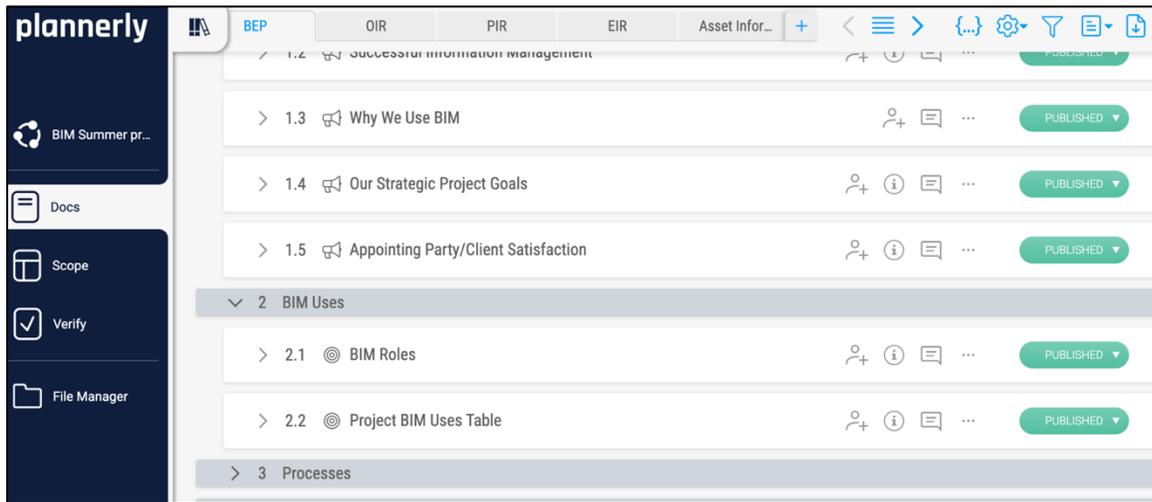


Figure A II. 7 BEP creation in Plannerly platform

Use Cases Application

Mobilization. The project structure is composed of the CDE, the different tools and software to realize the UC and the process of bringing together all. Catenda, the CDE chosen for the project, has been set up. This CDE platform allowed to collaborate during the project by regrouping all the stakeholders, sharing their models and ensure a good communication thanks to BCF integration in the shared models. It also helped in project management through error management. The whole project process has been defined, ensuring to work in a standard procedure and control the deliverables quality (see Figure A II. 8).

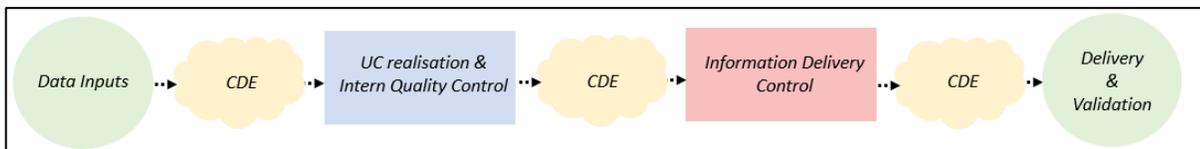


Figure A II. 8 Use Case application workflow

- Data input: Necessary data for each UC must be shared in the CDE in an open data format, i.e., PDF plans, IFC and XLM UC's IDS.
- UC realization & Quality Control: Then each team was able to carry out the activities concerned by the use cases by retrieving the information available in the CDE. Each final deliverable was then imported back into the CDE, still in an open data format, i.e. IFC or XLSX, after internal team quality checks (software version, model implementation coordinate, software language, number of errors indicated by the software).
- Information delivery control: the deliverables are retrieved from the CDE and compared with the IDS and initial requirements.
- Validation: In a real project, deliverables are finally submitted to the customer for approval.

Collaborative information production & Information model delivery.

This phase concerns the realization and delivery of the different UC applied in this project. Several PIM were produced in this phase and assembled into the AIM. The development of the PIM for the UC of “*Modelling of existing and new building design*” is described below as an example.

As a first step, the requirements for the assets specific to these use cases and impacting the data for the modelling, were transcribed into an IDS. This IDS was developed using the property and attribute definitions of the bSDD with the help of the Plannerly platform. The IDS PDF report and the architect's DWG drawings were then transmitted via Catenda. In a second phase, the modelling team consulted these files to create the 3D model in Revit and export it in IFC format. An internal quality check is then carried out based on a list of points to watch (software version, model implementation coordinate, software language, number of errors indicated by the software). The IFC file, which constituted the PIM for this use case, was then uploaded to Catenda for checking by the collaborators concerned, who submitted comments in BCF format. Finally, the IFC 3D model data was also checked by the production team using IDS via the Plannerly platform. A final stage was represented in the

process below, which concerned the final verification of the PIM IFC model by the customer (see Figure A II. 9). Once the validation was done, the PIM could be integrated in the AIM.

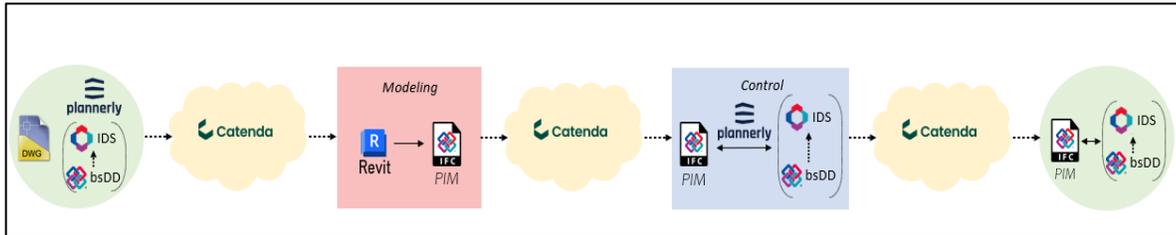


Figure A II. 9 Modelling workflow

Reporting

Closing the project. The project closing firstly results in this presented paper, providing technical feedback of the project concerning the application of the openBIM and ISO processes. In another study for the same conference, feedback concerning the learning process to master these concepts has been detailed.

5. Discussion

The objective of this project was to develop an artifact that could help BIM practitioners implement an openBIM approach, in accordance with the ISO 19650 series of standards. Through DSR, a process based on the steps of the standard combining openBIM principles and ISO 19650 was proposed. The artifact is a first point of reflection on the value of this approach. It demonstrates the relevance of continuing to work on ISO 19650 and openBIM, which are still in their infancy. Information management and interoperability are key issues to ensure the smooth running of projects. ISO 19650 provides a structure to guide professionals in managing the information produced and required in projects. The standard provides a framework for the exchange of information for each phase of the project and suggests working with open data to ensure its smooth use. Several open data formats exist, the most well known in the field of BIM being IFC and allow different software agents producing different native formats to communicate with each other. The openBIM approach,

based on the use of IFCs, offers concepts and guidelines to ensure the exchange of information in an interoperable way. As presented in the literature review section, ISO and openBIM are increasingly being studied and perceived as reference standards for the sector that is undergoing its digital transformation.

However, the literature offers few proven solutions to ensure an interoperable approach adapted to ISO 19650, which will allow all the potential benefits to be reaped. Adegun (Adegun, 2022) address this issue, proposing an approach based on the COBie, openBIM format usable in a context of exchange of equipment maintenance data. ISO is involved in this study to help define maintenance requirements to facilitate the completion of the Cobies sheets. The IFC format is also used to represent geometric objects and ensure interoperability. Patacas and al. (Patacas, Dawood, & Kassem, 2020) presents a solution to verify AIMs more easily, thanks to the definition of AIR structured as an IDM. This solution, which is like the IDS, allows the AIM to be checked automatically by machines. Its AIMs are fed with IFC files for graphical data and Cobie files for non-graphic data.

These studies demonstrate the value of using open data with ISO 19650 to ensure effective information management in projects. However, these approaches are applied for the use of facility management only, and do not cover the entire life cycle of assets. The ISO19650 standard has the potential to bring together all project stakeholders, just like the BIM philosophy. However, its use today shows emerging issues of segmentation, where some actors may be omitted when defining requirements (Jang & Collinge, 2020). Also, open data is presented through file formats only and not as a whole. It is therefore important to emphasize the importance of adopting a holistic vision bringing together stakeholders from the beginning of projects. Thus, the framework presented in this study suggests an approach where data is not only transmitted by open file format but also accessible, valid, and verified. The approach proposed here exploits open data to ensure synergy between stakeholder activities. In their study McGinley and al. (McGinley et al., 2023) framework is like the ISO process shown in **Fig. 3** but goes less into the details of how to apply openBIM concepts. The study therefore makes a key contribution advance discussion on standardizing project

information management. The artifact resulting from the study provides professionals with a first applied example that can serve as a reference. This also implies that professionals will need to be trained in each of these concepts. As this is still an embryonic topic, it is encouraged that this study to be repeated, and the framework reworked for other projects to clarify the concepts and guidelines of the openBIM-ISO 19650 approach.

The present study has provided some initial lessons on the various concepts applied. In the order of the process presented in Figure 4, the first element is the definition of the project needs, with OIR, PIR, AIR and EIR. These concepts, which come from the ISO standard, present difficulties to appropriate. The boundaries between OIR, PIR and AIR are sometimes thin and can lead to confusion. The artifact of the study proposes that OIRs reflect the primary objectives of the organization. PIRs should articulate project objectives and milestones, and AIRs should present asset requirements in the form of verifiable criteria. Thus, OIRs are defined for the organization, which can relate to its entity or portfolio of projects, and then PIRs are defined to describe and complement how OIRs are translated for a particular project. Once the OIR and PIR have been defined, it is possible to find out which use cases will meet the objectives of the project, because the UCs meet specific objectives. Then, these UCs, describing the processes to be implemented, should make it possible to define the AIRs that the project needs. However, the structures of the use cases today do not provide precision on the AIRs to be defined and few developed UCs are available. Working on standard UCs is essential to achieve a solid process. After defining the AIRs, it is possible to define the IDSs of the project assets. IDSs can be defined through bSDD using an API, but not many software are available that include bSDD APIs and therefore it is necessary to have programming knowledge to create them. Following UCs and AIRs, EIRs need to be defined. EIRs should be placed centrally in the management of project information as they will be used to define contractual exchanges between project stakeholders. These EIRs are the link between the "data planning" part, made by the definition of the OIRs, PIRs and AIRs, and the "production of data" that will be carried out in the PIMs for the delivery models and AIM for the asset operation models. The whole process is presented according to the authors' understanding and requires some time to understand and appropriate. The authors are aware

and have testified that their understanding of the standard may differ from that of other experts and therefore calls for further discussion on clarifying the definitions of the various terms and concepts mentioned here.

The DSR methodology applied in this project has provided an innovative process that contributes to both the advancement of BIM project management practices and knowledge in this field. In fact, the methodology's relevance cycle was achieved through an Ex-Ante evaluation. The standards chosen for the project had to respond to the issues raised by the study, i.e., improve information management and avoid interoperability problems in the project. The development cycle was validated by assessing its internal validity, to ensure that the ISO 19650 and openBIM frameworks maintained their functions, objectives, and terminologies even after combination. Also, the software used had to be compatible with open data. Finally, the artifact was validated by an Ex Poste-evaluation of the rigor cycle, by carrying out a framework application simulation confirming the compatibility of the two standards. The process demonstrates that using the concepts put forward by BuildingSMART enables optimum application of the ISO standard. The proposed artifact is therefore an advance in knowledge proposing a process, coordinating, and optimizing all existing ones.

6. Conclusion

This study concerns the implementation of a construction project testing the combined application of ISO19650 and openBIM. Using the ISO19650 guidelines, requirements were first defined using the OIR, PIR, AIR and EIR concepts. Once the framework of production and information exchange requirements had been established, the students were able to carry out the various MIP production phases. To support information management and address the issue of interoperability, the project process incorporated openBIM concepts: UC, IFC, bSDD, API, open file format and IDS. Future professionals will thus be able to familiarize themselves with the use of current and possibly future industry standards. From this study, an artefact has been proposed for the application of openBIM concepts during the various stages of ISO19650.

The study has limitations. One of those is the lack of validation of the proposed artifact, due to time constraints. Also, the conditions of the study, i.e., the realization of the project in a university context, prevent the artifact from being a generalizable solution. Finally, as discussed previously, the proposed framework is based on ISO19650 concepts which require interpretation and expert validation for ensuring a consensus in the use. In the future, it would be desirable to carry out this study in a real project context where the solution can be tested with professionals who can give concrete ways to improve the process. Furthermore, more time could be devoted to this stage and in particular to the definition of AIRs, which would enable a more complete IDS to be produced. The integration of the bSDD within the 3D model could also be tested in order to facilitate the definition of the IDS requirements and their verification. In addition, a real case study considering an entire project should be conducted so that all the stages of ISO19650 can be reproduced and the entire process tested.

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