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INTEGRATING BUILDING INFORMATION MODELING AND LIFE CYCLE ASSESSMENT IN THE EARLY AND DETAILED BUILDING DESIGN STAGES

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INTÉGRATION DE L'ANALYSE DU CYCLE DE VIE DANS LES MAQUETTES NUMÉRIQUES DE BÂTIMENTS DÈS LES PREMIÈRES ÉTAPES DE CONCEPTION

MÉMOIRE

PRÉSENTÉ

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LIST OF SYMBOLS AND UNITS

A	Surface area, m2
E	Electricity consumption, W
R	R-value, m2 K/W
T	Temperature, K
t	Time, h
Q	Building heating load, W
η	Heating system efficiency

RÉSUMÉ

Au début de la phase de conception d'un bâtiment, il y a beaucoup d'incertitudes dues au manque d'informations sur les matériaux et les procédés utilisés. Par conséquent, les concepteurs ne peuvent quantifier les impacts environnementaux des bâtiments pour évaluer la performance environnementale de leurs choix de conception à ce stade précoce. Ce travail vise à rendre possible la réalisation d'analyses du cycle de vie (ACV) à partir de la maquette numérique (BIM – building information model) d'un bâtiment au cours des étapes préliminaires (LOD100) et détaillées (LOD300) de la conception de celui-ci. Pour pouvoir le faire, le premier objectif du projet est la constitution d'une base de donnée fonctionnelle permettant d'identifier l'ensemble des options possibles pour un assemblage non défini précisément, comme c'est le cas lors des premières étapes de conception. Ceci permet de déterminer l'impact de cet assemblage à une étape préliminaire de conception, même sans connaître sa composition exacte. Le second objectif est d'appliquer la méthode développée à l'étude de cas d'immeuble résidentiel au Québec (Canada) aux niveaux préliminaire et détaillé de conception. Le BIM est réalisé avec Revit, et l'ACV avec openLCA. Pour convertir les données sortantes de Revit en données entrantes utilisables pour réaliser une ACV avec OpenLCA, la base de données fonctionnelle a été développée. Cette base de données comprend l'ensemble des assemblages de construction avec leurs différentes couches et l'ensemble des matériaux possibles que l'on trouve couramment dans les bâtiments résidentiels au Québec. La base de données ecoinvent a été utilisée comme source de données d'inventaire du cycle de vie pour chaque matériau. Pour gérer l'incertitude de l'information au stade LOD100, une fonction de probabilité a été attribuée à chaque matériau pour chaque couche de chaque assemblage. Les résultats de cette étude pourraientt guider les concepteurs de bâtiments dans l'évaluation environnementales de leurs conceptions, permettant de sélectionner des matériaux plus durables pour chaque assemblage et de réduire ainsi les impacts environnementaux du bâtiment. L'approche développée dans le cadre de cette étude est actuellement en train d'être intégrée à un outil qui permettra de réaliser automatiquement l'ACV de batiments lors de la création des maquettes numériques BIM.

Mots-clés: Bâtiment résidentiel; analyse du cycle de vie (ACV); modélisation des informations sur le bâtiment (BIM); LOD100; LOD300.

ABSTRACT

The building sector contributes to the acceleration of ongoing climate change due to the fact that considerable amounts of energy and material are required in different building stages. Massive developments in response to population growth and the low energy efficiency of existing buildings aggravate the situation. It is therefore necessary to change the design of new buildings to decrease their environmental impacts.

To quantify the environmental impacts of a building during its lifetime, life cycle assessment (LCA) is a common technique. The required data for LCA are mainly building materials, their production processes and their amounts. On the other hand, building information modeling (BIM) is a computer-based approach that contains the required building information. Therefore, different studies have been done to quantify the environmental impacts of buildings by integrating BIM and LCA. However, almost all these studies are conducted in the detailed design phase or LOD300. Integration of BIM and LCA at early design stage or LOD100 would be also useful because decisions are still simple to change as compared to LOD300 stage. It is, however, challenging since a lot of information and details are not available.

The main aim of this project is to develop a method to integrate BIM and LCA in both the early and detailed building design stages to be applied in a residential building in Canada. The BIM is conceptual in LOD100 stage, and building information for use in LCA is limited. To address these challenges, a database including all building assemblies, sub-assemblies, layers and materials was created. This functional database covers all possible options for each common building assembly used in residential buildings in Québec, Canada. The functional database was also completed by matching each material to a related ecoinvent life cycle inventory (LCI) dataset. In the functional database, each layer has different material options. Therefore, a probability distribution is used for each material to run an LCA model using the Monte Carlo simulation method. After creating the BIM in the early design stage with Revit software, the BIM file outputs are then matched with the LCA inputs through the functional database. The LCA conducted with openLCA by introducing the required data for all building stages. The integration of LCA and BIM is also implemented in the detailed building design stage to compare the early design stage results. This process is much more straightforward since the types and quantities of all materials are specified at this stage. The functional database developed in this project is currently being integrated with a software namely UBUBI to automatically extract required data from Revit to LCA software and integrate BIM and LCA.

Keywords: Residential building; life cycle assessment (LCA); building information modeling (BIM); LOD100; LOD300.

CHAPTER I INTRODUCTION

1.1 Environmental impacts of buildings

According to global environmental statistics and measurements, climate change due to the acceleration of human activities has become the most critical challenge of the Earth's system. In order to fight and control the irreversible consequences of climate change, all sectors must reduce the greenhouse gas emissions related to their products and services (Dansgaard *et al.*, 1993; Solomon *et al.*, 2009).

The building sector contributes to the acceleration of ongoing climate change due to the need of considerable amounts of energy and material through different stages from material production to end of life. Building material production includes producing and transporting required materials for building construction. A lot of raw materials and significant amounts of energy are needed in this stage. In the construction stage, energy in form of fossil fuels and electricity is consumed to be used for excavation and installation processes. Fossil fuels or electricity are required in the operation stage for heating, ventilation, and cooling (HVAC) systems. Different home appliances and lightings also need electricity in this stage. Due to different maintenance and renovation processes, some materials are again replaced in the operation stage. Finally, energy is required for building demolition to destroy the building and transport materials to landfill and recycle sites (Donham *et al.*, 1989; Pérez-Lombard *et al.*, 2008).

According to this description, it could be found that more than 38% of annual global greenhouse gas emissions are produced by buildings (Basbagill *et al.*, 2013; Sbci, 2009). The new huge constructions in response to the population growth and the low energy efficiency of existing buildings make this condition worse. Therefore, the new design buildings and the existing buildings conservation should be modified to decrease the building environmental impacts. It is noted that the environmental impacts of existing buildings are important as the building operation is the critical stage in terms of the energy consumption and the CO2 emission (Wang *et al.*, 2011). A range of methods are possible including the application of energy optimization policies in the building operation stage and the use more sustainable materials in building production and renovation (Iyer-Raniga et Wong, 2012; Kumar *et al.*, 2015). It would be useful for designers to evaluate the effects of their design adjustments on future building performances in the early design stage or LOD100 level of development because decisions are still simple to change as compared to the detailed design stage or LOD300 development stage. However, there are a lot of uncertainties in this stage due to the lack of information on building materials and processes. Therefore, designers cannot usually quantify the environmental impacts of the buildings to evaluate the environmental performance of their designs at this early stage (Lee *et al.*, 2015; Schade *et al.*, 2011).

1.2 Life cycle assessment (LCA) overview

To facilitate the decision-making process during building design, it is vital to quantify the environmental impacts of a building during its lifetime. Life cycle assessment (LCA) is a widespread technique to evaluate the environmental impacts of products and services. It considers all material and energy inputs, as well as human health and ecological impacts, over all stages in a service life (Jolliet *et al.*, 2010). Different software were developed for general LCA, including SimaPro and openLCA (OpenLCA ; SimpaPro).

The method consists of four different analytical steps based on the ISO 14040 including: (1) the goal and scope definition, (2) the life-cycle inventory creation, (3) the life cycle impact assessment, and (4) interpretation. Fig. 1.1 shows all LCA steps used in this project.

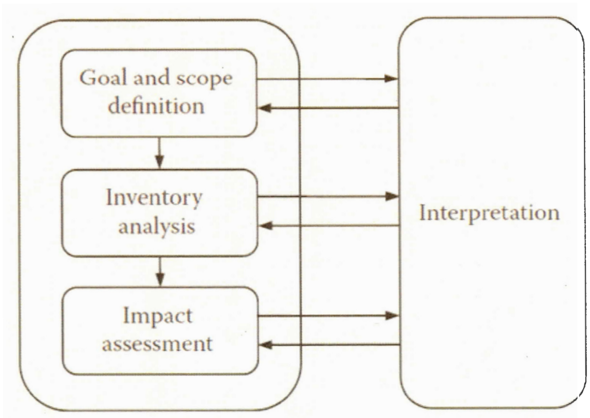

Figure 1.1: LCA framework based on ISO 14040 (ISO, 2006)

In a building, LCA evaluates environmental impacts of processes, products or services during the building lifetime stages including extraction and processing of raw materials, manufacturing and fabrications, transportations and distributions, usage and reuse, maintenance and conservation, recycling and final disposal (Khasreen, M. M. *et al.*, 2009).

Research findings have been implemented by applying LCA to different buildings (Anand et Amor, 2017; Basbagill *et al.*, 2013; Soust-Verdaguer *et al.*, 2017). Specific software to calculate the impact assessment of buildings (e.g. Athena, BEES, EQUER, etc. (Athena ; BEES ; EQUER)) serve to simplify the process. The main goal of the studies is to find the best construction and conservation processes and materials to minimize building energy consumption and environmental impacts (Asif *et al.*, 2007; Zabalza Bribián *et al.*, 2009; Zabalza Bribián *et al.*, 2011). The whole building LCA were implemented for all stages during building lifetime including building materials production, construction, operation, maintenance, and end of life (Anand et Amor, 2017; Basbagill et al., 2013; Soust-Verdaguer et al., 2017). These works were implemented in different countries including European countries, North America, Asia and Australia (Anand et Amor, 2017; Cabeza *et al.*, 2014; Soust-Verdaguer *et al.*, 2017). According to the overall methodology used by these studies, three important LCA factors can be concluded as follows.

(1) Type of analysis: Three types of analysis have been used in LCA. Firstly, the comparative analysis of the building energy consumption. (Pérez-Lombard *et al.*, 2008; Zabalza Bribián *et al.*, 2011). Secondly, the material-based comparative studies which evaluate the LCA of different materials in whole or an assembly of building (Guggemos Angela et Horvath, 2005). Thirdly, a whole building LCA which covers all environmental impacts of different building phases including pre-use, use, and demolition phases (Kylili *et al.*, 2017).

(2) Functional unit: The most popular functional unit in building LCA is building area (Anand et Amor, 2017).

(3) System boundaries: This parameter is specified important process in the LCA during the building life span. The most common case is cradle to grave which covers all building stages.

In 2015, Kumar et al. implemented a LCA study in the residential building in Vancouver (BC, Canada) for a 50-year lifespan. They considered four typical residential building including "High Rise Apartment (HRA)", "Low Rise Apartment (LRA)", "Single family Attached House (SAH)", and "Single family Detached House (SDH)". The operational energy consumption of each building was simulated by DesignBuilder software. The LCA analysis goal and scope was to evaluate the life cycle energy use and environmental impacts of these buildings. The functional unit used in this study was 1 m^2 of floor area of a house over its lifetime. A combination of the Athena Impact Estimator (Athena IE) for building and US EPA's TRACI method was used to evaluate the environmental impacts in the LCA modeling (Kumar *et al.*, 2015).

However, almost all these works were conducted in the detailed design phase or LOD300. At this stage, many important design decisions (e.g. building assembly, material types) have already been made. Therefore, LCA results for this stage do not affect the design decisions and only describes the environmental impacts of the final building. In order to make better decisions by changing the building design to decrease the environmental impacts, LCA should be used in the early building design (conceptual phase) or LOD100 stage. One of the most challenging points of this LCA study is the need for information and details that are not available at LOD100. These required data are mainly building materials, their production processes and their amounts. Beside this limitation, different factors could also increase the LCA uncertainty, as follows:

- It is hard to estimate the building lifetime to be used in LCA study. Noted that different studies have been used different values from 50-60 years (Anand et Amor, 2017; Kumar *et al.*, 2015; Soust-Verdaguer *et al.*, 2017).
- During building operation stage, there may be changes including materials and functionality in building maintenance and renovation processes.
- Many of building environmental impacts happen during its operational phase, and it is hard to predict them in the design phase.

1.3 Building information modeling (BIM)

To facilitate LCA, studies have relied on different computer-based building models (Soust-Verdaguer *et al.*, 2017). The models could easily provide the different building details used in the LCA model. Building digitization approach is among the computer-based approaches that contains all the required information for different technical building disciplines, including architectural, structural, mechanical and electrical systems (Khasreen, M. *et al.*, 2009; Kylili *et al.*, 2017).

Building information modeling (BIM) is a digital representation of a building's technical characteristics. It is a 3D digital model that includes all physical and functional details. It provides the building industry with different opportunities to share building information with all related groups, from designers to technicians, during a construction service life. The process leads helps mitigate the different challenges between design and construction groups (Ding *et al.*, 2014; Eastman *et al.*, 2011). Different BIM software such as Revit, Bentley, Vico and ArchiCAD (Azhar, 2011; Lee *et al.*, 2015) have been developed.

BIM file is initially created based on the building conceptual design, the site map, the building code requirement, and the owner expectations. This model usually consists of limited building assemblies and materials. The designers do not usually set any specific materials for the building components at LOD100 and prefer to postpone making these decisions. To complete the BIM and reach the detailed design stage, it is necessary to specify all plans, sections, elevations and details of the building with accurate information. The Revit materials and families or the manufacturer Revit families can be used to create more detailed model. The more the details presented, the more the accuracy BIM file. In the final stage, all created components will be assembled beside each other to create the whole model of the building. The final model includes all details and components of the building by using a bottom-up approach. Revit software can also calculate the building cooling and heating loads.

1.4 Integration of BIM and LCA

To quantify a building's environmental impacts, LCA requires data on all the components' materials. The model contains technical building information, and these required data could be extracted from the BIM file. Therefore, the environmental impacts of the buildings may be quantified by integrating BIM and LCA models. The method would be helpful to compare different building design and component options from an environmental perspective. Different studies were conducted to simultaneously consider LCA and BIM in order to reduce the construction challenges and environmental impacts of buildings.

In 2011 Wang et al., implemented a whole LCA by using BIM of a university building in Midwest, MY, USA. The building material quantities and specifications were extracted from BIM file to be used in Ecotect as a building energy simulator. LCA study was then carried out to only determine the CO_2 emission of building different materials. They excluded the building demolition and maintenance stages. A sensitivity analysis was also presented by using this method on five parameters including: indoor temperature set, wall type, R-values for exterior wall, roof, basement wall, and building orientation. The results showed that the building operation is the critical stage in terms of the energy consumption and the CO_2 emission (Wang *et al.*, 2011).

In 2012, Kulahcioglu et al. described the necessity of considering environmental assessment of United States building industry to reduce its negative impacts on environment. Therefore, they presented a prototype software for 3D analysis of LCA covering the whole construction process in design phase. They presented that how the accuracy of LCA process depends on the quality and availability of data from all phases of a building design. This prototype adopts IFC-based BIM and integrates it with LCA processes. They also used GABI to implement life cycle analysis of the imported building components by using the ecoinvent database. Since this methodology was designed for their BIM software, it cannot be applied to extract data from Revit to LCA tools. This limitation makes this methodology incomplete for integration of BIM and LCA for using in all consultant companies (Kulahcioglu *et al.*, 2012).

The combining of LCA and energy efficiency simulation tools was implemented in 2012 by Iyer-Raniga and Wong. The methodology was applied for eight residential heritage buildings in Victoria, Australia with different envelopes, structural framework, construction, age and climatic locations. After evaluation the primary energy consumption and life cycle environmental impacts, different intervention strategies were developed to identify which strategy has the most effect on building performance and energy consumption reduction in these buildings. (Iyer-Raniga et Wong, 2012).

In 2012, Jrade and Abdulla attempted to demonstrate the challenges of integrating BIM and LCA tools in the early building design stage. The Industry Foundation Classes (IFC) database is then used to link the Revit file and Athena EcoCalculator. However, the methodology used to match data between Revit and Athena has different limitations. For instance, it is not general enough to apply to an entire building since only two single assemblies, including a wall and door, were modeled (Jrade et Abdulla, 2012).

In 2013, Basbagill et al. tackled different challenges of the LCA and BIM integration in the early building design stage. DProfiler software is used as the BIM tool instead of Revit due to its much simpler structure. Also, eQUEST and SimaPro are used for energy simulation and the LCA study, respectively. To generate unknown information in the early building design, the Uniformat 2010 classification system is first used to categorize different building assemblies in the BIM file. Then, the material quantities of each assembly are calculated using different formulas developed by Beck Technology, a consultant company. However, the formulas include limited assemblies and materials lists. The energy construction, operational energy and demolition stages are ignored in the LCA. Also, the thermal effect of each material (e.g. R-value) on the heating and cooling load of the building is not considered (Basbagill *et al.*, 2013).

However, so far, there have been lots of limitations and unresolved issues remain. There are also technical challenges:

- Lack of integration of BIM and LCA in the early building design stage (LOD100) (Basbagill *et al.*, 2013)
- Lack of information in the LOD100 stage in the BIM model (Basbagill *et al.*, 2013)
- Lack of alignment between the BIM material database and LCA tools (Soust-Verdaguer *et al.*, 2017)
- Lack of an automatic data extractor from BIM to LCA (Soust-Verdaguer *et al.*, 2017)

1.5 Project objectives and motivation

The main objective of this project is to develop a method to integrate BIM and LCA in both early and detailed building design stages in order to cover all aforementioned limitations connecting BIM and LCA in the LOD100 stage. In LOD100 stage, many decisions related to building component selection are usually postponed until the detailed design stage. Therefore, there are many uncertainties in terms of the types and quantities of building assemblies and materials. The BIM is conceptual, and building information for use in LCA is limited. To address these challenges, a database including all building assemblies, sub-assemblies, layers and materials will be created. This functional database covers all possible options for each common building assembly used in residential buildings in Québec, Canada. The functional database is also completed by matching each material to a related ecoinvent life cycle inventory (LCI) dataset. In the functional database, each layer has different material options. Therefore, a probability distribution is used for each material to run an LCA model using the Monte Carlo simulation method. The integration of LCA and BIM is also implemented in the detailed building design stage to compare the early design stage results. This process is much more straightforward since the types and quantities of all materials are specified at this stage.

Therefore, the main objective of this study is to achieve the following sub-objectives:

- Objective 1: Developing a technique to investigate environmental impacts of different building materials in order to find the best option from environmental perspective
- Objective 2: Developing a functional database covering all possible options for each common building assembly used in residential buildings in Québec, Canada
- Objective 3: Integrating BIM and LCA in LOD100 stage of a residential building in Québec, Canada
- Objective 4: Integrating BIM and LCA in LOD300 stage of a residential building in Québec, Canada

The results of this work could be interesting for decision-makers and stakeholders in building industry, especially in Québec, Canada. The methodology presented in this work can be used to find the best sustainable layers and materials for different building components. The functional database developed in this project is going to be used in a software namely UBUBI to automatically extract required data from Revit to LCA software and integrate BIM and LCA.

1.6 Project outline

This report includes three chapters. Chapter one is an introduction to the study. The LCA and BIM approaches are briefly discussed in this chapter. Also, a literature review is presented on different BIM and LCA studies in buildings. In Chapter two, the methodology, case study, and results of this project is presented. The content of this chapter is based on a paper which has been submitted to Building and Environment journal. Finally, Chapter three wraps up the project presenting the study conclusion and future work.

CHAPTER II INTEGRATING BUILDING INFORMATION MODELING AND LIFE CYCLE ASSESSMENT IN THE EARLY AND DETAILED BUILDING DESIGN STAGES

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ABSTRACT

In the early building design stage, there are a lot of uncertainties due to the lack of information on materials and processes. Therefore, designers cannot quantify the environmental impacts of the buildings to evaluate the environmental performance of their designs at this early stage. In this work, Life cycle assessment (LCA) and building information modeling (BIM) are carried out in the early and also detailed building design stages. The method is applied to a residential building in Québec, Canada. The BIM is conducted with Revit, and the LCA with openLCA. To prepare the Revit outputs as the appropriate inputs of the LCA model, a functional database was developed. It includes all building assemblies, layers and possible materials commonly found in residential buildings in Québec. The ecoinvent database was used as source of life cycle inventory (LCI) data for each material. To manage information uncertainty in the early design stage, a probability function was assigned to each material. At the detailed design stage, all materials types and quantities were specified in BIM file, which was used in LCA study. The environmental impacts of the building stages and assemblies were calculated to determine the best options for building assemblies from an environmental perspective. A process that could guide building designers in the environmental assessments of their designs, making it possible to select more sustainable materials for each assembly and thus reduce the environmental impacts of the building.

Keywords: Residential building; life cycle assessment (LCA); building information modeling (BIM); LOD100; LOD300.

Nomenclature:

A	Surface area, m^2
E	Electricity consumption, W
R	R-value, m^2 K/W
T	Temperature, K
t	Time, h
Q	Building heating load, W
η	Heating system efficiency

2.1 Introduction

According to global environmental statistics and measurements, climate change due to the acceleration of human activities has become the most critical challenge of the Earth's system. In order to fight and control the irreversible consequences of climate change, all sectors must reduce the greenhouse gas emissions related to their products and services (Dansgaard *et al.*, 1993; Solomon *et al.*, 2009).

The building sector contributes to the acceleration of ongoing climate change due to the fact that considerable amounts of energy and material are required in different building stages, including material production, construction, operation, maintenance and demolition (Fumo *et al.*, 2010; Pérez-Lombard *et al.*, 2008). Each year, buildings produce over 38% of global greenhouse gas emissions (Basbagill *et al.*, 2013; Sbci, 2009). Based on the environmental reports released by the UN, the building sector is responsible for over 40% of global energy use. The biggest percentage of building energy consumption occurs as part of operations during building lifetimes (Basbagill *et al.*, 2013; Fumo *et al.*, 2010; Sbci, 2009). Massive developments in response to population growth and the low energy efficiency of existing buildings aggravate the situation. It is estimated that the sector's greenhouse gas emissions will approximately double in the next 20 years if decision-makers do not change the governing policies that regulate new and existing buildings (Sbci, 2009).

It is therefore necessary to change the design of new buildings and building renovations to decrease their environmental impacts. A range of methods are possible including the application of energy optimization policies in the building operation stage and the use more sustainable materials in building production and renovation (Iyer-Raniga et Wong, 2012; Kumar *et al.*, 2015). However, the more energy efficient the buildings become, the more important the relative contribution of the other life cycle stages, in particular the material production. One challenge is the fact that no tool allows designers to evaluate the effects of their design adjustments on future building performances in the early design stage (or LOD100 level of development), when decisions are still simple to change as compared to the detailed design stage (or LOD300 development stage). There are a lot of uncertainties in this stage due to the lack of information on building materials and processes. Therefore, designers cannot usually quantify the environmental impacts of the buildings to evaluate the environmental performance of their designs at this early stage (Lee *et al.*, 2015; Schade *et al.*, 2011).

To facilitate the decision-making process, it is vital to quantify the environmental impacts of a building during its lifetime. Life cycle assessment (LCA) is a widespread technique to evaluate the environmental impacts of products and services. It considers all material and energy inputs, as well as human health and ecological impacts, over all stages in a service life (Jolliet *et al.*, 2010). Different software were developed for general LCA, including SimaPro and openLCA (OpenLCA ; SimpaPro). Research findings have been implemented by applying LCA to different buildings (Anand et Amor, 2017; Basbagill *et al.*, 2013; Soust-Verdaguer *et al.*, 2017). Specific software to calculate the impact of buildings (e.g. Athena, BEES, EQUER, etc. (Athena ; BEES ; EQUER)) serve to simplify the process. The main goal of those studies and tools is to find the best construction and conservation processes and materials to minimize building energy consumption and environmental impacts (Asif *et al.*, 2007; Zabalza Bribián *et al.*, 2009; Zabalza Bribián *et al.*, 2011). However, almost all these works were conducted in the detailed design phase or LOD300. At this stage, many important design decisions (e.g. building assembly, material types) have already been made. Therefore, LCA results at this stage do not affect the design decisions and only describes the environmental impacts of the final building.

In order to make better decisions by changing the building design to decrease the environmental impacts, LCA should be used in the early building design (conceptual phase) or LOD100 stage. One of the most challenging points of LCA studies is the need for information and details that are not available at LOD100, in particular the building materials, their production processes and their amounts.

To facilitate building LCA, studies have relied on different computer-based building models (Soust-Verdaguer *et al.*, 2017). The models could easily provide the different building details used in the LCA model. Building digitization approach is among the computer-based approaches that contains all the required information for different technical building disciplines, including architectural, structural, mechanical and electrical systems (Khasreen, M. *et al.*, 2009; Kylili *et al.*, 2017).

Building information modeling (BIM) is a digital representation of a building's technical characteristics. It is a 3D digital model that includes all physical and functional details. It provides the building industry with different opportunities to share building information with all related groups, from designers to technicians or manager, during a construction service life. The process helps mitigate the different communication and harmonization challenges between design, construction and management groups (Ding *et al.*, 2014; Eastman *et al.*, 2011). Different BIM software such as Revit, Bentley, Vico and ArchiCAD have been developed (Azhar, 2011; Lee *et al.*, 2015). The BIM process differs depending on whether the building is in the operational or design stage. The former is more challenging due to the lack of data accessibility. To obtain the data required to create the BIM of existing buildings, it is necessary to gather data or assume certain information. The BIM file is gradually created in the building design stage, from the early (LOD100) to the detailed (LOD300) stages. The BIM file is initially created based on the building's conceptual design, the site map, the building code requirements and the owner's expectations. The model generally consists of limiting building assemblies and materials. The facade surface area, roof surface area, building area, and number of floors are specified at LOD100 but there are still many unknown parameters. The designers do not usually set any specific materials for the building components at LOD100 and prefer to postpone these decisions. The schematic design stage (LOD200) is created by adding more details and non-geometric information to the conceptual design stage (LOD100). Then, an accurate model is developed in the detailed design stage (LOD300) by defining specific assemblies and subassemblies, material types with specific quantities, building size, shape and orientation, building energy systems and building utility systems.

To quantify a building's environmental impacts, LCA requires data on all the components' materials. The BIM contains technical building information, and these required data could be extracted from the BIM file. Therefore, the environmental impacts of the buildings may be quantified by integrating BIM and LCA models. The method is helpful to compare different building design and component options from an environmental perspective. Different studies were conducted to simultaneously consider LCA and BIM in order to reduce the construction challenges and environmental impacts of buildings (Kulahcioglu *et al.*, 2012; Wang *et al.*, 2011). However, so far, there have been lots of limitations and unresolved issues remain. There are also technical challenges:

- Lack of integration of BIM and LCA in the early building design stage (LOD100(Basbagill *et al.*, 2013));
- Lack of information in the LOD100 stage in the BIM model (Basbagill *et al.*, 2013): In LOD100 stage, many decisions related to building component selection are usually postponed until the detailed design stage. Therefore, there are many

uncertainties in terms of the types and quantities of building assemblies and materials;

- Lack of alignment both in term of nomenclature and in term of detail level between the BIM material database and LCA tools (Soust-Verdaguer *et al.*, 2017);
- Lack of an automatic data extractor from BIM to LCA (Soust-Verdaguer *et al.*, 2017).

In 2012, Jrade and Abdulla attempted to demonstrate the challenges of integrating BIM and LCA tools in the early building design stage. The Industry Foundation Classes (IFC) database was then used to link the Revit file and Athena EcoCalculator. However, the methodology used to match data between Revit and Athena has different limitations. In particular, it is not general enough to be applied to an entire building since only two single assemblies (wall and door), were modeled (Jrade et Abdulla, 2012).

In 2013, Basbagill et al. tackled different challenges of the LCA and BIM integration in the early building design stage. DProfiler software was used as the BIM tool instead of Revit due to its much simpler structure. Also, eQUEST and SimaPro were used for energy simulation and the LCA study, respectively. To generate unknown information in the early building design, the Uniformat 2010 classification system was first used to categorize different building assemblies in the BIM file. Then, the material quantities of each assembly were calculated using different formulas developed by Beck Technology, a consultant company. However, those formulas included only a limited number of assemblies and materials lists. The construction energy, operational energy and demolition stages were also ignored in the LCA. (Basbagill *et al.*, 2013).

The main aim of this paper is to develop a method to integrate BIM and LCA in both the early and detailed building design stages. All the aforementioned limitations to connecting BIM and LCA in the LOD100 stage are covered, except for the development of an automatic data extractor from the BIM file, which is being covered by a complementary project and is not the focus of the present paper. To address these challenges, a database including all building assemblies, sub-assemblies, layers and materials is created. A framework based on this database to be used in LCA at the LOD 100 stage is proposed. Then, this framework is applied to the case study of a residential building. The results of this case study at the LOD 100 stage is then put in perspective with the results obtained for the same building at the LOD 300 stage.

2.2 Methodology

2.2.1 Functional database development

In order to be able to proceed to LCA at the earlier design stage, there is a need to deal with underspecified assemblies. For example, the information given can be the size and position of a wall, but without any information about the type of layers and materials used in this wall, it is not possible to perform LCA. Therefore, there is a need to document all the reasonable possibilities of assemblies and materials for this wall in order to be able to quantify the impact with the corresponding uncertainty related to not knowing more precisely what kind of wall it is. To do so, a functional database is created, compiling all the different options for each assembly and all the corresponding life cycle inventories. The functional database developed in the present project covers all possible options for each common building assembly used in residential buildings in Québec, Canada. In the present project, the model is created by Revit software, which is the most widely used software in BIM. However, the methodology developed could be applied to any other BIM software. The ecoinvent 3.3 database was used to find appropriate life cycle inventory data for different building materials and services as it is the most comprehensive and transparent life cycle inventory database currently available.

The first step is to develop a materials list that includes all the building materials commonly used in residential buildings in Québec (e.g. concretes, woods, aggregates, insulations, etc.). Then, the different characteristics of each material (e.g. density and R-value), are gathered from different resources (EngineeringToolBox ; Lawton *et al.*, 2010; Zarr *et al.*). This information is helpful in unit conversion between Revit material takeoff and LCA databases and in the energy analysis stage. Finally, a process from the ecoinvent 3.3 life cycle inventory database is matched with each material on the materials list.

Each material from Revit is then matched with a related dataset in the ecoinvent 3.3 life cycle inventory (LCI)database. The integration of the information extracted from Revit and the ecoinvent database is challenging due to the mismatch between the Revit materials list and ecoinvent database: the Revit materials list is not as specific or detailed as the ecoinvent database. Some of the Revit materials have been matched with more than one ecoinvent processes when several options were available. Moreover, the units of the Revit materials are not usually the same as those defined in the ecoinvent database. To manage these technical challenges, the data extracted from BIM and the ecoinvent processes to be used in the openLCA software have been bridged using expert judgement, Canadian construction codes and standards, and the material properties. Note that ecoinvent LCI data for Québec or North America were used in this study. However, the data for other locations with similar processes and technologies may have also been used.

The next step is to develop a functional database that includes all building assemblies, layers and materials. All building components are classified into six different assemblies, including foundation, floor and ceiling, roof, door and window, exterior wall and interior wall. Then, the different layers of each assembly are specified, including different possible technologies and options by means of technical architectural resources (Athena ; ecoinvent ; U.S.DepartmentofEnergy).

Finally, the specification of each assembly layer option is matched with possible materials by using the materials list.

Fig. 2.1 and Table 2.1 illustrate an example of this process for the exterior wall assembly. The process for perlite material is as follow:

- Perlite is one of the filler options used in exterior walls of residential buildings in Québec, Canada.
- The density and R-value of perlite are presented in Table 2.1 according to technical resources.
- Perlite is matched with the ecoinvent process as shown in Table 2.1. There is mismatch between Revit and ecoinvent unit for perlite. The Revit unit is volume (m^3) while ecoinvent is mass (kg). Therefore, the density value is used for matching the Revit output and ecoinvent process for perlite.

The same process is then done for all material options of each assembly. Hence, when "a wall" is defined in Revit, all the different wall options can be modeled using LCA and a distribution of potential impact can be calculated for this underspecified wall.

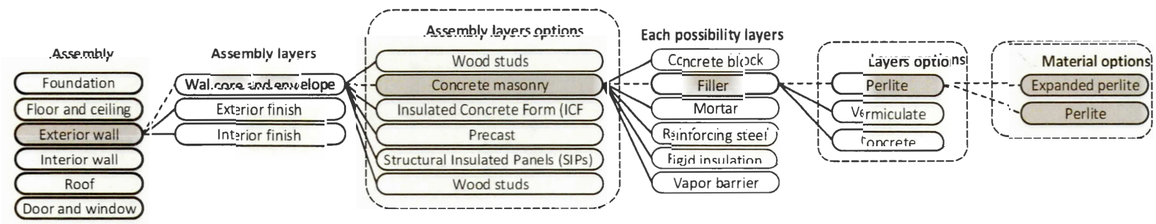

Figure 2.1: Example (filler layer of an exterior wall) of the data mapping used in this study

Table 2.1: Filler sub-layers and material options inside the functional database

Layer	Layer options	Materials	Density kg/m^3	R-value h ft^{2}F/Btu in (m.K/W)	Reference Product Name[c]	unit
Filler	Concrete	concrete, 20MPa	2334†	1.43 (0.826) •	concrete, 20MPa	m^3
Filler	Concrete	concrete, 25MPa	2334*	1.43 (0.826) •	concrete, 25MPa	m^3
Filler	Concrete	concrete, 30-32MPa	2324*	1 (0.577) •	concrete, 30-32MPa	m^3
Filler	Concrete	concrete, 35MPa	2324*	0.83 (0.479) •	concrete, 35MPa	m^3
Filler	Concrete	concrete, 40MPa	2386*	0.67 (0.387) •	concrete, 35MPa	m^3
Filler	Concrete	concrete, 50MPa	2386*	0.67 (0.387) •	concrete, 50MPa	m^3
Filler	Concrete	concrete, 60MPa	2240*	0.52 (0.300) •	concrete, 50MPa	m^3
Filler	Concrete	concrete, normal	2380*	0.075 (0.043) •	concrete, normal	m^3
Filler	Perlite	expanded perlite	90*	3.12 (1.80) ■	expanded perlite	kg
Filler	Perlite	perlite	90*	3.12 (1.80) ■	perlite	kg
Filler	Vermiculite	vermiculite	272*	2.27 (1.311) ■	expanded vermiculite	kg

† (U.S.DepartmentofEnergy), * (Athena), • (Archtoolbox), ■ (MULTI-WYTHE), [c] (ecoinvent)

By doing this for all the existing assemblies, a functional assembly database is created that includes all the building components. The structure of this database is like a tree starting from main building assemblies and ending to the ecoinvent processes. Each layer could be mapped to different materials depending on technology and application.

The final stage of the data mapping is to match the Revit assemblies to this assembly-based database. In this study, the step was carried out manually. The outputs of the Revit quantity takeoff and ecoinvent database are thus bridged.

Seeing as LCA implementation is not possible without this data mapping, this stage is critical to BIM-LCA integration. A careful work of data mapping was therefore conducted. It is worth noting that this data mapping approach could be used to develop any automatic data extractor in the future, which is currently done in a parallel project at CIRAIG (international reference centre for the life cycle of products processes and services) group.

Different probability distributions could be used in this stage. In this study, the uniform distribution was applied for model simplification.1000 Monte Carlo iterations are carried out, where a specific realization of the assembly or building design is randomly sampled for each iteration. The assembly types and materials all consider with an equal probability of being sampled, representing a situation with absolutely no knowledge of the final design options. The impacts are evaluated using the Impact 2002+ impact assessment method (Humbert *et al.*, 2005; Jolliet *et al.*, 2003).

2.2.2. Development of a framework to apply LCA at the LOD 100 stage

To implement building LCA in the early and detailed design stages, the service life of the building is categorized into four different stages: material production, construction, operation and maintenance and demolition.

After creating the BIM in the early design stage of the studied building (LOD100) with the Revit software, the BIM file outputs are generated as types and quantities of all building materials for each assembly. The results are then matched with the LCA inputs through the functional database. The LCA is then conducted with openLCA by introducing the required data for all building stages, from raw materials extraction to end of life.

Assumptions have to be made when data are lacking, which is the case at the LOD100 stage. These assumptions which are necessary to make the LCA, are mentioned in the following sections for the different building stages.

2.2.2.1 Production

This stage includes the environmental impacts of building materials production and their transportation from the manufacturer to the building sites. The data mapping plays a key role in this stage. The material production stage rests on the building data classification developed in the functional database. The quantity of each assembly is calculated from the quantity take-off outputs of the Revit software. However, as in the early building design stage, there are many unknown parameters that are important in LCA. In this case, probability functions are used to perform the LCA modeling based on the Monte Carlo simulation as illustrated on figure 2.2

Besides material production, data collection or assumptions have to be made for the transportation of each of the materials to the building site. By default, a possible assumption of 100 km can be made. It is noted that transportation was not the focus of the present project and this assumption should be considered as a proxy and could be refined.

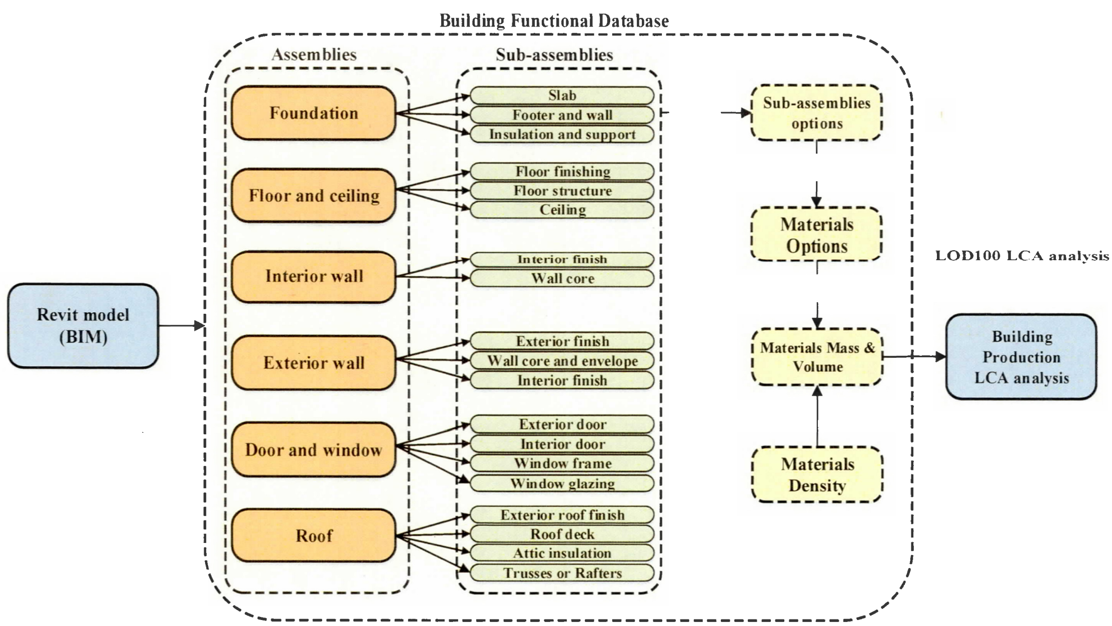

Figure 2.2: Linking BIM and LCA at the early design stage using the building functional database to determine the probability functions of each material

2.2.2.2 Construction

The construction process includes the installation and excavation energy and the amount of building material waste which have to be quantified. Both fossil fuels and electricity are required in the building installation and excavation stages. The possible values for these energy demands can be assumed when no data is available by considering a uniform probability. According to gathered information from different building contractor companies in Québec, the mean values of electricity and diesel required for building construction are approximately 60 MJ and 15 MJ per building area, respectively. By considering a uniform probability, three different amounts of construction energy are assumed per building area including 10% lower of mean values, the mean values, and 10% higher of the mean values.

Since the material types are not specified in the LOD 100 stage, a constant percentage value for material discarded during construction is assumed for all building materials. Therefore, three scenarios with 5%, 10% and 15% of the total building materials assumed to be wasted in the building construction stage (Bakshan *et al.*, 2015). These wasted materials are considered transported to the landfill site, with an assumed distance of 100 km.

2.2.2.3 Operation and maintenance

According to the literature, the operation and maintenance step is the most critical stage in the LCA of buildings. Therefore, it is critical to accurately consider all environmental impacts of this stage. Three major sources generate environmental impacts in this stage: energy required for home electrical appliances, lighting and heating, ventilation, and cooling (HVAC), water and the material replacement process throughout the building's service life.

The energy type for heating has to be assumed as well as the potential presence of a cooling system. If no information is available at this LOD100 stage, assumptions can be made based on the probability of occurrence of the different heating systems and cooling systems in the region where the building is to be constructed.

To calculate heating energy in the detailed design stage (LOD300), energy simulation can be implemented by Revit since all materials are known. However, at LOD100 stage, the energy consumption is estimated by calculating the heating load of the building based on equation 1:

$$Q_{Heating} = \left(\frac{A_{Wall}}{R_{Wall}} + \frac{A_{Roof}}{R_{Roof}} + \frac{A_{Window}}{R_{Window}}\right) \times (T_{Inside} - T_{Outside}) \qquad (1)$$

Where Q, A, R, and T are the building heating load, the surface area, R-value and temperature. The R-value may be calculated depending on each assembly material. Therefore, there is uncertainty surrounding this parameter since the building materials are not clearly defined at the LOD100 stage.

Assumptions have to be made for the inside and outside temperatures of the building. Statistics indicate that most Canadian households set their home temperature between 20°C and 22°C during the daytime when they are at home and awake during the colder months. The average indoor temperature in this study is therefore assumed to be 22°C during winter. Moreover, the average outdoor temperature in this study is assumed to be -10°C based on the average high and low temperatures during the cold months in Québec and Montréal [14]. Based on Eq. (1), the annual energy consumption for the heating system is estimated using equation 2:

$$E_{Heating} = \frac{Q_{Heating} \times t}{\eta} \qquad (2)$$

Where η is the heating system efficiency, and t is the time in hours for four cold months (2 880 h/yr) during the building's life cycle. Here, the lifetime of the building also has to be assumed in order to be able to quantify the impacts of the operation and maintenance phase. A proxy value of 60 years can be used by default.

The quantity of electricity required for home appliances, hot water, and lighting is highly dependent on the consumption patterns of the members of the household. By default, three amounts of annual electricity consumption can be considered for low-, medium- and high-demand consumers, including 50 kWh, 100 kWh and 150 kWh per m^2 at the LOD100 level. Alternatively, if assumptions are already made on the type of appliances available in the building, the Hydro-Québec statistics can be used to set the average required electricity for those appliances (HydroQuebec). It is noted that the Quebec grid mix is selected as electricity production process from ecoinvent during LCA study of building operation phase.

The approach for daily water consumption is the same as for electricity demand. Three daily water consumption patterns can be taken into account in the residential buildings including 50, 100 and 150 liters per person in the LOD100 stage. Alternatively, the average water consumption in Québec can be used as a default value.

In the maintenance stage, the material replacement is considered based on the service life of each material. For instance, the painting is carried out every 5years, the mortar is replaced every 15 years and the insulation remains for the entire life cycle of the building. Table 2.2 illustrates the life expectancy of different building materials or components (InterNACHI). The LCA of the operation and maintenance stage in the LOD100 is carried out by considering uniform probability for each item using the Monte Carlo method.

Table 2.2: Life expectancy of different building materials or components (InterNACHI)

Building material or component	Life expectancy (years)	Building material or component	Life expectancy (years)
Fibre cement finish	30	Rough carpentry	120
Membrane	22.5	Rough finish carpentry	60
Support finishes	60	Wood siding	20
Painting	5	Floor finishing	20
Masonry finish	60	Vinyl siding	60
Mortaring	15	Non-rigid insulation	120
Metal sheet	120	Gypsum board	30
Stone finish	60	Aggregate	100
Stucco	60	Asphalt shingle finish	20
Vinyl siding	60	Clay roof tile	120
Rigid insulation	120	Concrete roof tile	120
Vapor barrier	100	Window frame	30
Concrete block	120	Window glazing	30
Filler	120	Exterior door	120
Reinforcing steel	120	Interior door	30
Cast in place	100		

2.2.2.4 End of life

The end of life stage consists of two parts: demolition and material disposal processes. In the demolition stage, the energy is the fossil fuel required to power the building deconstruction machines. The material disposal stage is modeled based on the building assembly classification. All probability functions are assumed for each assembly layers and materials as in the material production stage. Two scenarios may be defined for material disposal, including transportation to landfill and recycling. Different amounts of recycling percentages may also be assigned depending on the material type.

The integration of LCA and BIM can of course also be implemented in the detailed building design stage (LOD300) to compare it to the early design stage results. This process is much more straightforward since the types and quantities of all materials are all specified at this stage.

2.3 Case Study

The aforementioned method was applied to the design process of a residential building in Québec, Canada in the LOD100 and in the LOD300 design phase. The case study is a four-storey multi-residential building consisting of 8 one-bedroom and 32 two-bedroom apartments. All building components were selected based on current Canadian building codes and standards. Fig. 2.3 shows the 3D model of the residential building developed for this study using Revit software.

As presented in Fig. 2.3, a conceptual design is created in the early design stage. This model includes the building's location, its shape and orientation and its total area and volume. No specific material type or quantity is specified in this level. However, certain information on the main assemblies may be extracted from the model, such as exterior wall surface area, height, total building surface area and roof surface area. Also, information on other assemblies may be estimated by making assumptions in this phase. For instance, the total surface area of windows is estimated by considering a 0.3 window to wall ratio.

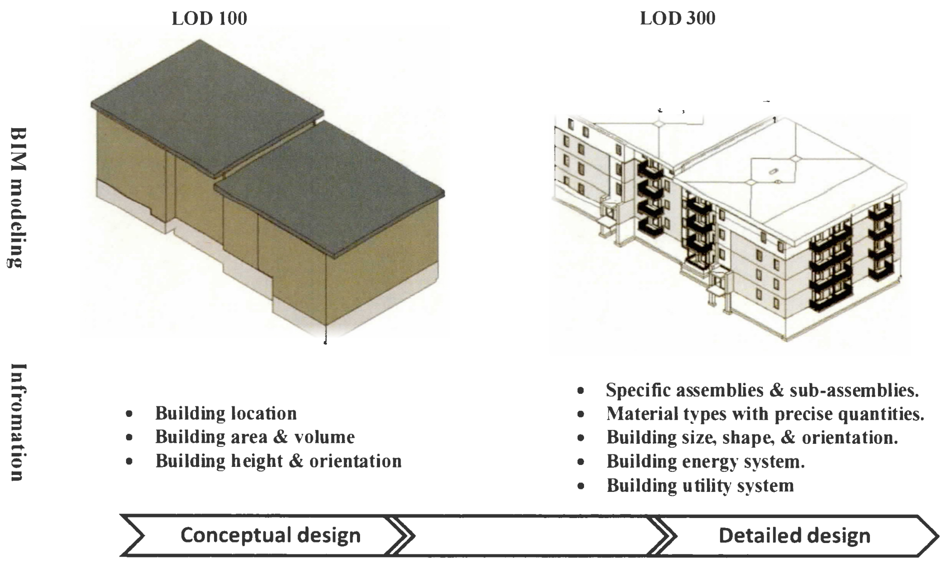

Figure 2.3: Revit model of the residential building in the LOD100 and LOD300 design phases

The following assumptions were made during LCA study for LOD 100 stage:

- Construction: all the existing possible options in Québec, Canada for the assemblies are considered equally probable with a uniform distribution. Two types of energies are required for this process including electricity and diesel burn in machines. As discussed before, the amount of energy assumed for these energies are considered as a uniform distribution of probability between 54 MJ, 60 MJ, and 66 MJ for electricity and 12.5 MJ, 15 MJ, and 18 MJ for diesel per building area. Three scenarios are also considered with 5%, 10% and 15% of the total building materials assumed to be wasted in the building construction stage (Bakshan *et al.*, 2015). These wasted materials are considered transported to the landfill site, with an assumed distance of 100 km.
- Operation and maintenance: The energy type considered for heating is electricity, no cooling is considered. According to Eq. (1), the annual quantity of energy considered for whole building heating system is dependent on R-value of materials of exterior walls, windows, and roof. The annual energy consumption for the heating system is estimated from 230e+6 to 245e+6 MJ/year. Also, the annual energy considered for appliances and lighting is a uniform probability distribution between 200 MWh, 400 MWh, and 600 MWh. By assuming 160 persons in the building, the annual water consumption is considered as a uniform distribution of probability between 2920 m^3, 5840 m^3, and 8760 m^3. It is noted that, in this study, the building lifetime is assumed to be 60 years.

For comparison purpose, the LCA of the same building was also conducted at the LOD 300 stage using the following assumptions:

- Production: The LOD300 model is developed based on the same structure as the LOD 100 and all layers and materials options in the LOD300 model are selected from functional database. Fig. 2.4 illustrates this process for different layers and options of exterior wall type-1 in the LOD300. This selection process is also implemented for all building assemblies in the LOD300 model.

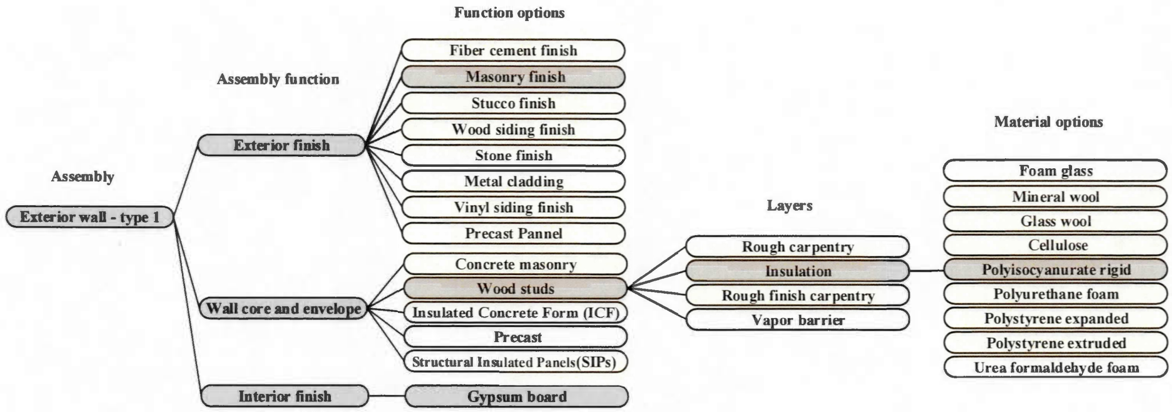

Figure 2.4: Selection process for layers of exterior wall type-1 in LOD300 from functional database

- Construction: The mean demand values from contractors of electricity and diesel required for building construction are assumed to be correct for LOD 300 case study. These values are 60 MJ and 15 MJ per building area for electricity and diesel, respectively. Also, the wasted materials are considered transported to the landfill site, with an assumed distance of 100 km.
- Operation and maintenance: Contrast to LOD 100 model, Revit energy simulation module can be used to estimate energy needed for heating system in LOD 300 stage. The internal temperature of the building is set to be 22°C for energy simulation process, and also, overall R-value of the building is calculated based on the building assemblies' layers. The average required electricity for home appliances, hot water, and lighting is set to 80 kWh/m^2 during LCA study in LOD 300 step using the Hydro-Québec statistics (HydroQuebec).

2.4 Results and discussion

2.4.1 Functional database

A comprehensive functional database has been developed for all the assemblies common in residential buildings of Québec. The methodology of this functional database is represented in section 2.2.1. In this functional database, all the existing options of materials are documented for all the layers and sub-layers of each assembly and each material has been matched with all the corresponding ecoinvent 3.3 processes considering an equal probability distribution. This distribution could ultimately be modified to better represent the current practices in the different regions of North America.

2.4.2 Case study at the LOD100 level

In this section, the LCA results are presented for the building in early design stage (LOD100). Fig. 2.5 shows the results of the LCA of the entire building as compared to its stages including material production, construction, operation and maintenance and end of life. As expected, the operation and maintenance stage is the most critical stage in the LCA study. This occurs because of the residential building's high energy demand throughout its life cycle for its heating system, applications, lighting etc. The environmental impacts of the operation stage could be reduced by applying different adjustments to the building, such as using renewable energy facilities, increasing the building thermal performance or decreasing the indoor temperature.

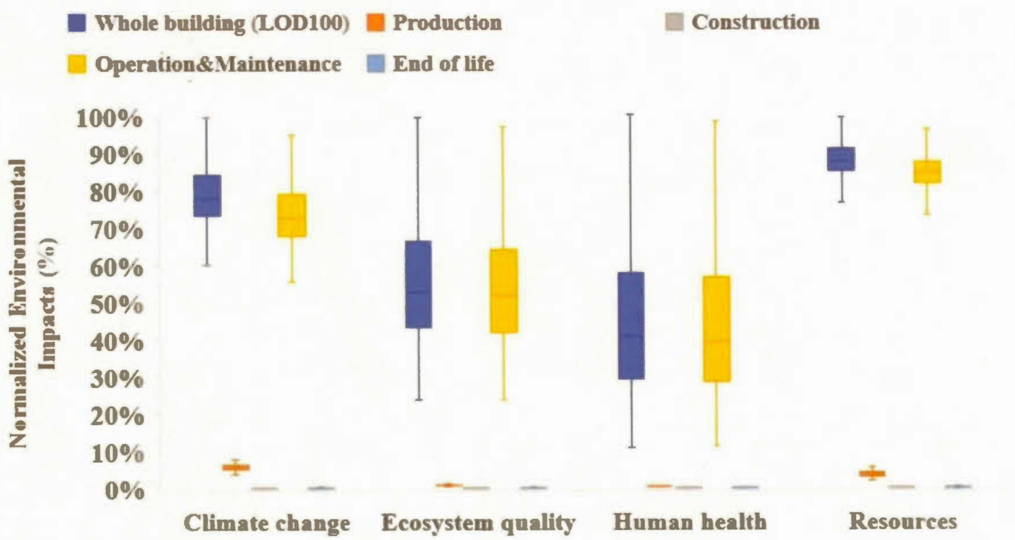

Figure 2.5: The LCA results for the entire building in LOD100 as compared to the building stages

According to Fig. 2.5, building materials production is another critical building stage. In the early design stage, designers cannot specify the building characteristics since there is no way to evaluate different options. It would be useful for them to have a tool to make decisions about assemblies and materials at this stage. To achieve this goal, a detailed LCA of the production stage is conducted for different assembly layers. Fig. 2.6 illustrates the comparison of the LCA results for different assemblies in the material production stage. As indicated, the foundation and exterior wall are the main sources of the building's environmental impacts in the material production stage. The main subassembly and material in the foundation assembly is concrete. A building's architecture generally cannot decrease or change the amount of foundation concrete in the early design stage because accurate calculations are only obtained later from the structure team. However, it is easier to make a decision about the exterior wall. To determine the best choice for the exterior wall in this project, a LCA is carried out by including different layers of the exterior wall.

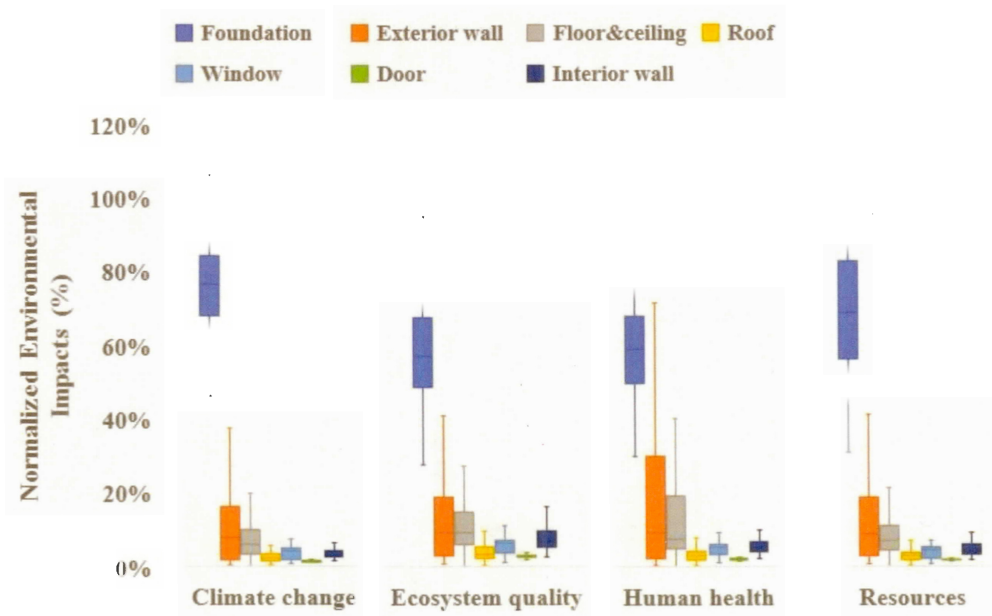

Figure 2.6: LCA results comparison between different assemblies in the material production stage normalize by production median

Fig. 2.7 illustrates the comparison of the LCA results for the exterior wall layers, including wall core, exterior finish and interior finish. It is obvious from the figure that the effect of the exterior and interior finish layers on the environmental impacts are negligible as compared to the wall core layer. This is because of the layer's considerable volume. Therefore, the LCA study continues to evaluate the best option for wall core layers.

Figure 2.8 shows the results of the LCA analysis for different wall core technologies. Wood studs and structural insulated panels (SIPs) are the best options for the wall core in this project. Concrete masonry and insulated concrete form (ICF) are the least interesting in this project.

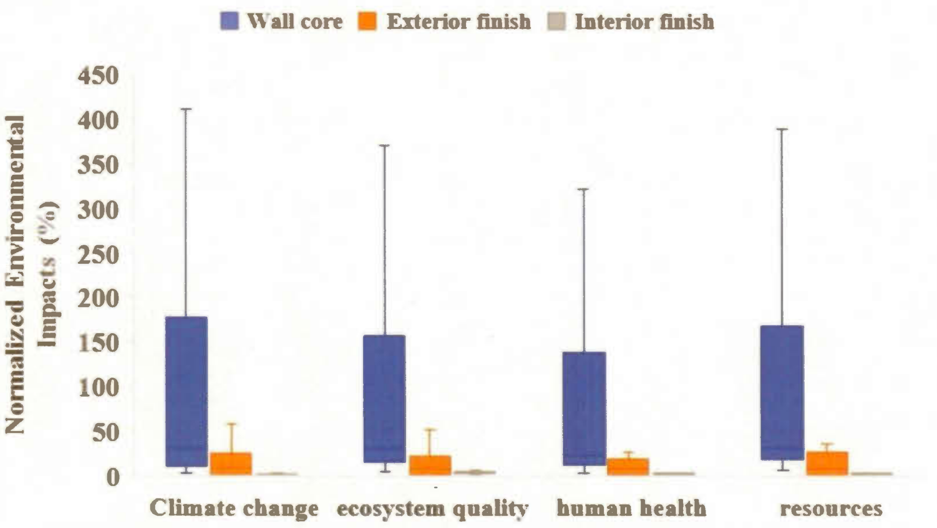

Figure 2.7: LCA results comparison between exterior wall layers, including wall core, exterior finish, and interior finish normalize by exterior wall median

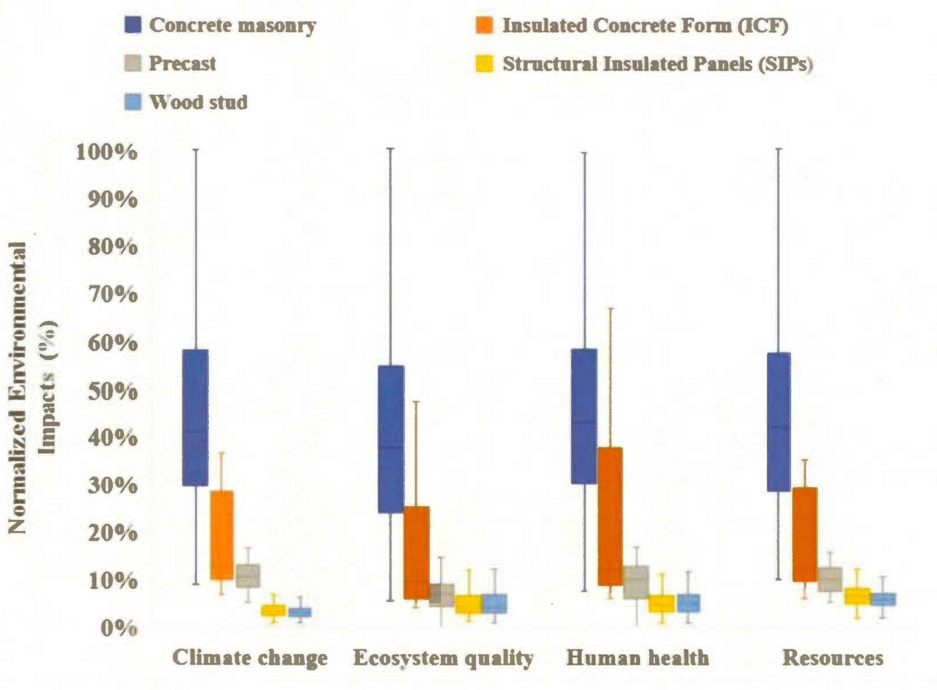

Figure 2.8: Comparative LCA results for different wall core options in the LOD100

The bottom line is that the process could be carried out for all assembly layers to provide architectural designers with feedback. It may be implemented at the end of the early design stage by manual or automatic data extractor from Revit model.

2.4.3 Case study: comparison between LOD100 and LOD300 levels

As expected, the LOD300 stage LCA impact is within the range of uncertainty of the LOD100 level LCA. As it is the case at the LOD100 level, the operation and maintenance stage generates a very large share of the building's environmental impacts. The material production stage is also significant but the effects of construction and end of life are not considerable. Figure 2.9 compares the LCA results of the LOD100 and LOD300 phases for the operation and maintenance and material production stages.

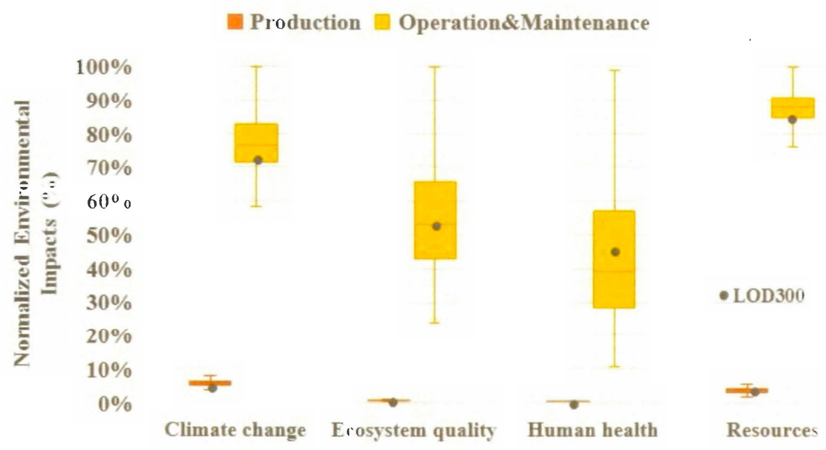

Figure 2.9: Comparison of the LCA results for the LOD100 and LOD300 phases

As can also be seen on this figure, the choices that were made by the designer at the LOD300 level are among the best possible choices in term of climate change and resources use. The comparison of LOD 100 and LOD 300 results between different assemblies in the material production stage are also represented in Fig. 2.6. As it can be seen, the LOD 300 trend for different assemblies are similar to the LOD 100 results.

Hence, we can highlight here that the use of LCA at the earlier design stage could help building designers to already estimate the environmental impacts of their designs at the LOD100 stage with the corresponding uncertainty. Moreover, the effects of different building design scenarios on the environment may also be compared, making it possible to select more sustainable materials for different building assemblies and modify the building to reduce its environmental impacts.

This study could prove useful for different building stakeholders including consultants, contractors, manufacturers, constructors, managers and owners since it provides them with certain environmental data to be used in their decision-making processes related to building design, construction and renovation. At the present stage, the functional database developed in the present project has to be used manually by LCA practitioners, but it aims at feeding a tool that will allow doing automatically life cycle assessment directly in BIM at any LOD level, hence better informing all the decision makers using BIM about the environmental consequences of their choices in real time.

2.5 Conclusion

The integration of life cycle assessment (LCA) and building information modeling (BIM) was carried out for a residential building in Québec, Canada. The BIM was created using Revit software, and the LCA was conducted with openLCA software. A functional database was developed to prepare the Revit outputs for the LCA model. It includes all building assemblies, subassemblies, layers and possible materials. The ecoinvent database was also used to allocate an appropriate process to each material to be applied in two early and detailed building design stages. In the early design stage, or LOD 100, a Monte Carlo approach was used to allocate the uncertainty of the materials in each assembly. In addition, in the detailed design stage or LOD 300, the detailed data from the BIM model was used to run the LCA model. The environmental impacts of different building stages and assemblies were calculated to determine the best building material options. This process could help building designers carry out environmental assessments of their designs and then select more sustainable materials for different building assemblies, leading to a reduction in the environmental impacts of the building.

The results show that the operation and maintenance stage is the most critical stage in the LCA study. This occurs because of the residential building's high energy demand throughout its life cycle for its heating system, applications, lighting etc. Moreover, by comparison of the LCA results for different assemblies and materials in the material production stage, it was shown that the foundation and exterior wall are the main sources of the building's environmental impacts in the material production stage. The simulation results for different wall materials also represent that wood studs and structural insulated panels (SIPs) are the best options for the wall core in this project. Concrete masonry and insulated concrete form (ICF) are the least interesting in this project.

Acknowledgment

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CHAPTER III CONCLUSION AND FUTURE WORK

The integration of life cycle assessment (LCA) and building information modeling (BIM) was carried out for a residential building in Québec, Canada. The BIM was created using Revit software, and the LCA was conducted with openLCA software. To prepare the Revit outputs to be appropriate inputs for the LCA model, a functional database was developed. This functional database includes all building assemblies, subassemblies, layers and possible materials. Also, the ecoinvent database was used to allocate an appropriate process to each material to be applied in two early and detailed building design stages. In the early design stage, or LOD100, a Monte Carlo approach was used to allocate the uncertainty of the materials in each assembly. Also, in detailed design stage or LOD300, the detailed data from the BIM model was used to run the LCA model. The environmental impacts of different building stages and assemblies were calculated to determine the best building material options. This process could help building designers carry out an environmental assessment of their designs and then select more sustainable materials for different building assemblies, leading to a reduction in the environmental impacts of the building.

The following suggestions could guide future work.

- An automatic data extractor to directly prepare information from a Revit file for use in an LCA model is currently under development at CIRAIG (international reference centre for the life cycle of products processes and services) group. This tool is based on the functional database developed in the present study.

- In this study, we used a uniform probability distribution to select possible assembly layers. However, it would be much more accurate to estimate this probability function based on data gathered from local architectures.
- A more accurate energy model would increase the model's accuracy. This model should be coupled with the building material selection process to change the R-values based on the building materials.
- A sensitivity analysis should be carried out to determine the parameters that most contribute to uncertainty.
- BIM and LCA could be integrated by considering other effective factors such as the initial and operational costs of different materials and energy sources. The model could prove useful to all stakeholders to optimize their decision-making processes.

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