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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 numerous uncertainties due to the lack of information on materials and processes. Designers therefore cannot quantify the environmental impacts of buildings in order to evaluate the environmental performance of their designs early on. In this paper, life cycle assessment (LCA) and building information modeling (BIM) are carried out in the early and 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 to 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 material types and quantities were specified in BIM file, which was used in the LCA study. The environmental impacts of the building stages and assemblies were calculated to determine the best building assembly options 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.

1. Introduction

According to global environmental statistics and measurements, climate change due to the acceleration of human activities has become the planet's most critical challenge. 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 [1,4].

The building sector contributes to the acceleration of ongoing climate change due to the fact that considerable amounts of energy and materials are required in different building stages, including material production, construction, operation, maintenance and demolition [5,6]. Each year, buildings generate over 38% of global greenhouse gas emissions [7,8]. Based on the environmental reports released by the UN, the building sector is responsible for over 40% of global energy use. The most significant percentage of building energy consumption occurs as part of operations during building lifetimes [5,7,8]. 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 [8].

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 of more sustainable materials in building production and renovation [9,10]. However, the more energy efficient buildings become, the more significant the relative contribution of their other life cycle stages, particularly material production. One challenge is the fact that no tool enables designers to evaluate the effects of their design adjustments on future building performances in the early design stage (or LOD 100 level of development) when decisions are still simple to change as compared to the detailed design stage (or LOD 300 development stage). There are numerous uncertainties in this stage due to the lack of information on materials and processes. Designers therefore cannot quantify the environmental impacts of buildings in order to evaluate the environmental performance of their designs early on [11,12].

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

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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

environmental impacts of products and services. It considers all material and energy inputs and human health and ecological impacts in every stage of a service life [13]. Different software were developed for general LCA, including SimaPro and openLCA [14,15]. Research findings have been implemented by applying LCA to different buildings [7,16,17]. Specific software to calculate the impacts of buildings (e.g. Refs. [18–20]; etc. [18-20]) serve to simplify the process. The main goal of these studies and tools is to find the best construction and conservation processes and materials to minimize building energy consumption and the environmental impacts [3,22,23]. However, almost all these studies were conducted in the detailed design phase or LOD 300. 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 describe the environmental impacts of the final building.

LCA should be used in the early building design (conceptual phase) or LOD 100 stage to make better decisions by changing the building design to decrease the environmental impacts. One of the most challenging points of LCA studies is the need for information and details that are not available at LOD 100, specifically building materials, their production processes and their quantities.

To facilitate LCA, studies have relied on different computer-based building models [17]. The models could easily provide the different building details used in the LCA model. Building digitization is among the computer-based approaches that contain all the information required for different technical building disciplines, including architectural, structural, mechanical and electrical systems [24,25].

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 and managers, throughout a construction's service life. The process helps mitigate the different communication and harmonization challenges between design, construction and management groups [26,27]. Different BIM software such as Revit, Bentley, Vico and ArchiCAD have been developed [11,28]. 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 (LOD 100) to the detailed (LOD 300) stages. The BIM file is initially created based on the building's conceptual design, site map, building code requirements and 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 LOD 100 but there are still many unknown parameters. Designers do not usually set any specific materials for the building components at LOD 100 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 (LOD 100). Then, an accurate model is developed in the detailed design stage (LOD 300) 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. Studies were conducted to simultaneously consider LCA and BIM in order to reduce the construction challenges and environmental impacts of buildings [30,31]. However, so far, there are numerous limitations and unresolved issues. There are also technical challenges:

- Lack of integration of BIM and LCA in the early building design stage (LOD 100 [7]);
- Lack of information in the LOD 100 stage in the BIM model [7]: in the LOD 100 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 terms of nomenclature and in terms of detail level between the BIM material database and LCA tools [17];
- Lack of an automatic data extractor from BIM to LCA [17].

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 [32].

In 2013, Basbagill et al. tackled different challenges in the integration of LCA and BIM 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 used to categorize different building assemblies in the BIM file. Then, the material quantities of each assembly were calculated using different formulas developed by consultant firm Beck Technology. However, the 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 [7]. It is also noted that the BIM and LCA combination could be used for evaluating the environmental impacts of only one building assembly or subassembly. For example, Panteli et al. recently applied this technique to develop a framework for building overhang design [33].

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 LOD 100 stage are covered, except for the development of an automatic data extractor from the BIM file, which is the focus of a complementary project. To address these challenges, a database including all building assemblies, sub-assemblies, layers and materials was created. A framework based on this database to be used in LCA at the LOD 100 stage was set out and then applied to the case study of a residential building. The results of this case study at the LOD 100 stage were then put into perspective with the results obtained for the same building at the LOD 300 stage.

2. Methodology

2.1. Functional database development

In order to be able to conduct the LCA at an earlier design stage, it is important to first look at the underspecified assemblies. For example, there may be information on the size and position of a wall but, without any information on the type of layers and materials used in this wall, it is not possible to carry out the LCA. Therefore, there is a need to document all the reasonable assembly and material options for the wall in order to quantify the impact and corresponding uncertainty related to not knowing exactly what type of wall it is. A functional database must therefore be created to compile all the different options for each assembly and all the corresponding life cycle inventories. The functional database developed as part of this project covers all possible options for each common building assembly used in residential buildings in Québec, Canada. Here, the model is created using Revit software, which is the most widely used software in BIM. However, the methodology could be applied to any other BIM software. The ecoinvent 3.3 database, the most comprehensive and transparent life cycle inventory database currently available, was used to find appropriate life cycle inventory data for different building materials and services.

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 [34-36]. This information supports 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 ecoinvent 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 were matched with more than one ecoinvent process 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 handle these technical challenges, the data extracted from BIM and ecoinvent processes to be used in the openLCA software were bridged using expert judgement, Canadian construction codes and standards and material properties. Note that ecoinvent LCI data for Québec or North America were used in this study. However, 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 [18,37,38].

Finally, the specifications of each assembly layer option are matched with possible materials using the materials list.

Fig. 1 and Table 1 illustrate an example of the process for the exterior wall assembly. The process for perlite material is as follows:

- 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 1 based on technical resources.
- Perlite is matched with the ecoinvent process, as shown in Table 1. There is mismatch between Revit and the ecoinvent unit for perlite. The Revit unit is volume (m^3) while ecoinvent is mass (kg). Therefore, the density value is used to match the Revit output and ecoinvent process for perlite.

The same process is then carried out for every material option for each assembly. When a wall is defined in Revit, all the different wall options may be modeled using LCA, and a distribution of potential impact may be calculated for the underspecified wall.

By doing this for all existing assemblies, a functional assembly database is created that includes all the building components is created. The structure of this database is like a tree, from main building assemblies and 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.

Because LCA implementation is impossible without this data mapping, this stage is critical to BIM-LCA integration. Careful data mapping was therefore conducted. It is worth noting that this data mapping approach could be used to develop any automatic data extractor (a parallel project is currently underway at the International Reference Centre for the Life Cycle of Products, Processes and Services (CIRAIG)).

Different probability distributions may be used at this stage. In this study, uniform distribution was applied to simplify the model. In total,1 000 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 assessed using the Impact 2002 + impact method. In this technique, all midpoint impacts are grouped into four end points including human health, ecosystem quality, climate change, and resources. The human health damage category consists of human toxicity, ionizing radiation, depletion of the ozone layer, respiratory effects of inorganic particular matter, and photooxidant formation. The climate change end point is calculated according to greenhouse gases emitted per person per year in Europe. The midpoint categories of the resources are the consumption of non-renewable primary energy and the extraction of minerals. Also, ecosystem quality consists of five midpoints including aquatic ecotoxicity, terrestrial ecotoxicity, aquatic acidification, terrestrial eutrophication, and land use [39,40].

2.2. Development of a framework to apply LCA in the LOD 100 stage

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

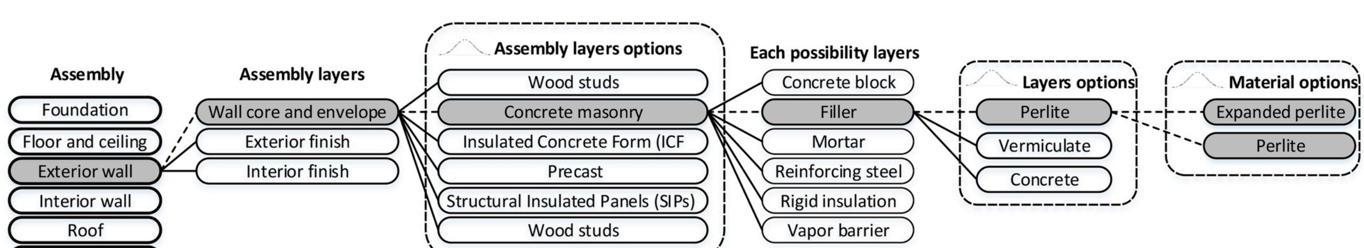

Fig. 1. Example (filler layer of an exterior wall) of the data mapping used in this study.

Table 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	unit
Filler	Concrete	concrete, 20 MPa	2334†	1.43 (0.826) ●	concrete, 20 MPa	m^3
Filler	Concrete	concrete, 25 MPa	2334*	1.43 (0.826) ●	concrete, 25 MPa	m^3
Filler	Concrete	concrete, 30–32 MPa	2324*	1 (0.577) ●	concrete, 30–32 MPa	m^3
Filler	Concrete	concrete, 35 MPa	2324*	0.83 (0.479) ●	concrete, 35 MPa	m^3
Filler	Concrete	concrete, 40 MPa	2386*	0.67 (0.387) ●	concrete, 35 MPa	m^3
Filler	Concrete	concrete, 50 MPa	2386*	0.67 (0.387) ●	concrete, 50 MPa	m^3
Filler	Concrete	concrete, 60 MPa	2240*	0.52 (0.300) ●	concrete, 50 MPa	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

† [38], * [18], ● [2], ■ [29], ○ [37].

demolition. It is worth to mention that it is hard to predict the behavior of the building users. Therefore, considering all building stages as the boundaries of LCA will cause different uncertainties, such as energy consumption, building life time.

After creating the BIM in the early design stage of the studied building (LOD 100) using 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 conducted with openLCA by introducing the required data for all building stages, from raw materials extraction to end of life.

When data are lacking, assumptions must be made. This is the case in the LOD 100 stage. The assumptions for the different building stages, which are necessary to conduct the LCA, are outlined in the following sections.

2.2.1. Production

This stage includes the environmental impacts of building material production and their transportation from the manufacturer to the building sites. 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 conduct the LCA modeling based on the Monte Carlo simulation, as illustrated on Fig. 2.

Besides material production, data collection or assumptions on the transport of each material to the building site are required. By default, the distance may be assumed to be 100 km. Transport was not the focus of this project, and the assumption should be considered a proxy that may be refined.

2.2.2. Construction

The construction process includes the installation and excavation energy and the amount of building material waste that must be quantified. Both fossil fuels and electricity are required in the building installation and excavation stages. When no data is available, the possible values for these energy demands may be assumed by considering a uniform probability. According to information collected from Québec contractors, 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,

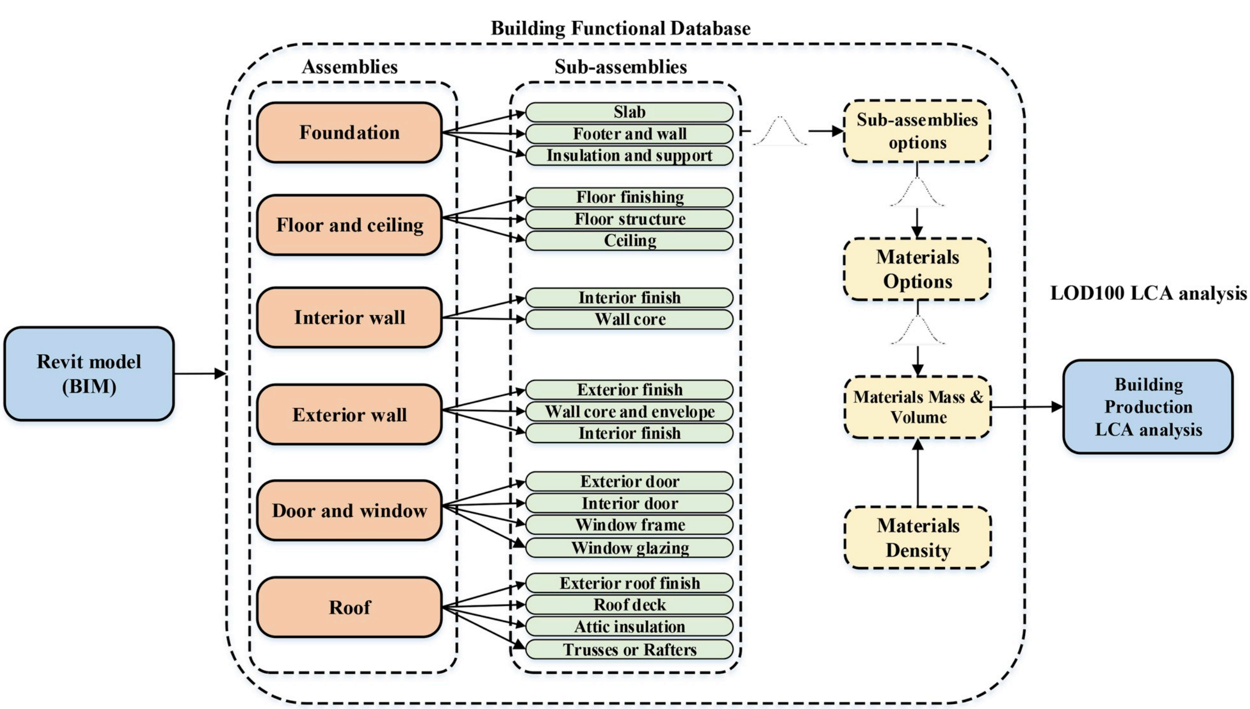

Fig. 2. Linking BIM and LCA in the early design stage using the building functional database to determine the probability functions of each material.

Table 2
Life expectancy of different building materials and components [18].

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		

including 10% lower than mean values, mean values and 10% higher than mean values.

Since the material types are not specified in the LOD 100 stage, a constant percentage value for materials discarded during construction is assumed for all building materials. Therefore, there are three scenarios with 5%, 10% and 15% of the total building materials assumed to be wasted in the building construction stage [41]. These wasted materials are considered transported to the landfill site, at an assumed distance of 100 km.

2.2.3. Operation and maintenance

According to the literature, operation and maintenance is the most critical stage in the LCA of buildings. Therefore, it is essential to accurately consider all the 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 must be assumed, as well as the potential presence of a cooling system. If no information is available at this LOD 100 stage, assumptions may be based on the probability of occurrence of the different heating and cooling systems in the region where the building is to be constructed.

To calculate heating energy in the detailed design stage (LOD 300), energy simulation may be implemented by Revit since all materials are known. However, at the LOD 100 stage, the energy consumption is estimated by calculating the heating load of the building according to Equation (1):

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

Where Q, A, R, and T are the building heating load, surface area, R-value and temperature. It is noted that the heating energy needed for ventilation and air leakage in the building is almost 1% of the building heating load and therefore it is assumed to be negligible in this paper. 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 in the LOD 100 stage.

Assumptions must be made for the building's indoor and outdoor temperatures. 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 in 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):

$$E_{Heating} = \frac{Q_{Heating} \times t}{\eta} \tag{2}$$

Where η is the heating system efficiency and t is the time in hours for

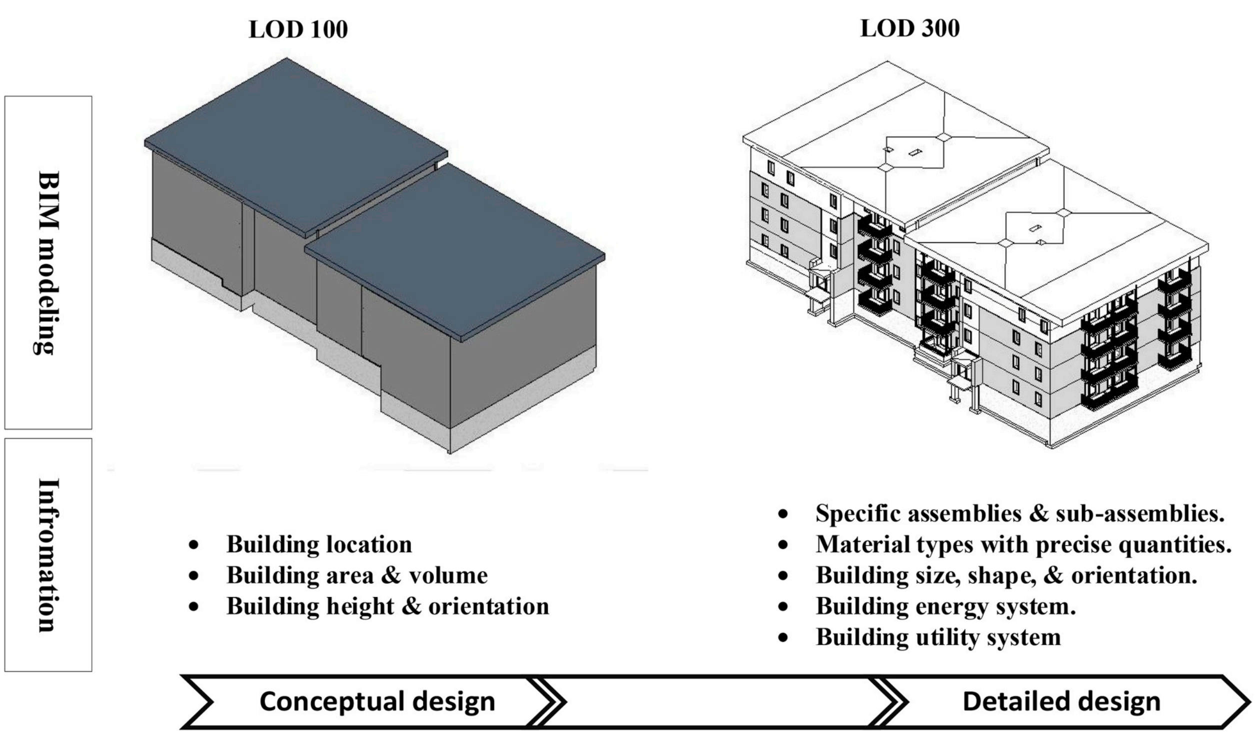

Fig. 3. Revit model of the residential building in the LOD 100 and LOD 300 design phases.

four cold months (2880 h/yr.) during the building's life cycle. Here, the lifetime of the building must also be assumed in order to quantify the impacts of the operation and maintenance phase. A proxy value of 60 years may be used by default.

The amount 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 may be considered for low-, medium- and high-demand consumers, including 50 kWh, 100 kWh and 150 kWh per m^2 at the LOD 100 level. Alternatively, if assumptions are already made on the types of appliances in the building, Hydro-Québec statistics may be used to set the average required electricity for each appliance [42]. The Québec 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. For residential buildings, three daily water consumption patterns may be taken into account, including 50, 100 and 150 L per person in the LOD 100 stage. Alternatively, the average water consumption in Québec may be used as a default value.

In the maintenance stage, material replacement is considered to be based on the service life of each material. For instance, e painting is carried out every 5 years, mortar is replaced every 15 years and the insulation remains for the entire life cycle of the building. Table 2 illustrates the life expectancy of different building materials and components (InterNACHI). The LCA of the operation and maintenance stage in the LOD 100 stage is carried out by considering uniform probability for each item using the Monte Carlo method.

2.2.4. End of life

The end of life stage consists of two parts: demolition and material disposal. 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 layer and material, as in the material production stage. Two scenarios may be defined for material disposal, including transportation to landfill and recycling. Different recycling percentages may also be assigned depending on the material type.

Of course, the integration of LCA and BIM may also be implemented in the detailed building design stage (LOD 300) to compare it to the early design stage results. This process is much more straightforward since the types and quantities of all materials are 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 LOD 100 and LOD 300 design phases. 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. 3 shows the 3D model of the residential building developed for this study using Revit software.

As presented in Fig. 3, a conceptual design is created in the early design stage. The model includes the building's location, shape, orientation total area and volume. No specific material type or quantity is indicated at this level. However, certain details 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.

The following assumptions were made for the LCA of the LOD 100 stage.

For comparison purposes, the LCA of the same building was also conducted in the LOD 300 stage using the following assumptions.

- Production: The LOD 300 model is developed based on the same structure as the LOD 100, and all layers and material options in the LOD 300 model are selected from the functional database. Fig. 4 illustrates this process for different layers and options of exterior wall type-1 in the LOD 300 model. This selection process is also implemented for all building assemblies in the LOD 300 model.

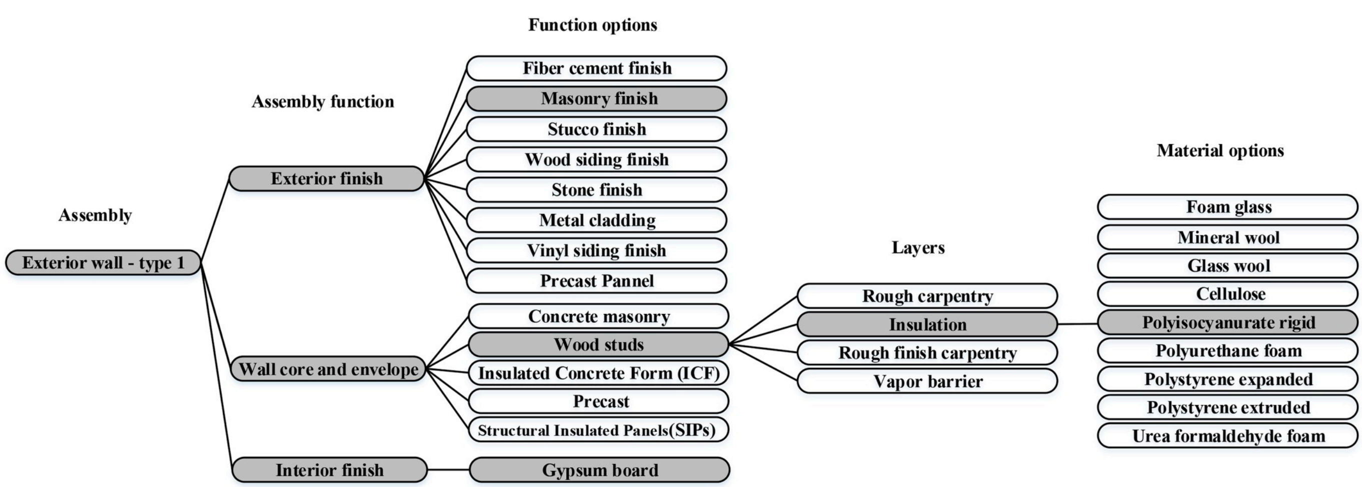

Fig. 4. Selection process for layers of exterior wall type-1 in LOD 300 from functional database.

- Construction: All 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 earlier, the amounts 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 [41]. These wasted materials are considered transported to the landfill site at 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 the entire building's heating system is dependent on the R-value of the materials of the exterior walls, windows and roof. The annual energy consumption for the heating system is estimated between 230e + 6 and 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. Assuming a building capacity of 160 persons, the annual water consumption is considered as a uniform distribution of probability of 2920 m^3, 5840 m^3 and 8760 m^3. In this study, the building lifetime is assumed to be 60 years.

- Construction: The mean demand values for the electricity and diesel required for building construction provided by contractors o are assumed to be accurate for the 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 at an assumed distance of 100 km.
- Operation and maintenance: In contrast to the LOD 100 model, the Revit energy simulation module may be used to estimate the energy required by the heating system in the LOD 300 stage. The internal temperature of the building is set to 22 °C for the energy simulation process. Also, the overall R-value of the building is calculated based on the building assembly layers. The average required electricity for home appliances, hot water and lighting is set to 80 kWh/m^2 in the LCA study in LOD 300 step using Hydro-Québec statistics [42].

3. Results and discussion

3.1. Functional database

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

3.2. Case study at the LOD 100 level

In this section, the LCA results are presented for the building in the early design stage (LOD 100). Fig. 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 (e.g. using renewable energy facilities, increasing the building thermal performance or decreasing the indoor temperature).

According to Fig. 5, building material 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 on assemblies and materials at this stage. To achieve this goal, a detailed LCA of the production stage is conducted for different assembly layers. Fig. 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 does not 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, an LCA was conducted by including the different layers of the exterior wall.

Fig. 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 is 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.

Fig. 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.

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 using manual or automatic data extractor from Revit model.

3.3. Case study: comparison between the LOD 100 and LOD 300 levels

As expected, the impact of the LOD 300 stage is within the range of uncertainty of the LOD 100 LCA. As is the case at the LOD 100 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. Fig. 9 compares the LCA results of the LOD 100 and LOD 300 stages for the operation and maintenance and material production stages.

As also seen on Fig. 9, the designer's choices at the LOD 300 level are among the best possible choices in terms of climate change and resource use. The comparison of LOD 100 and LOD 300 results between

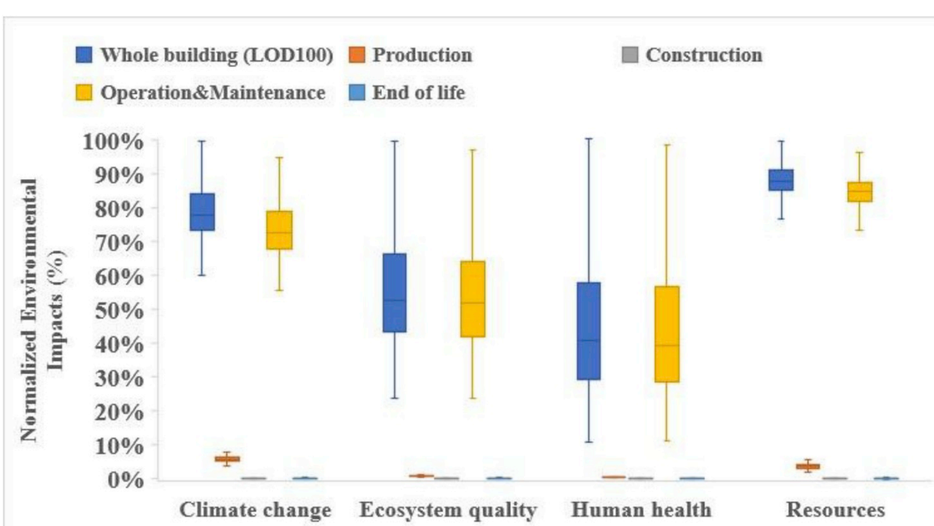

Fig. 5. The LCA results for the entire building in LOD100 as compared to the building stages.

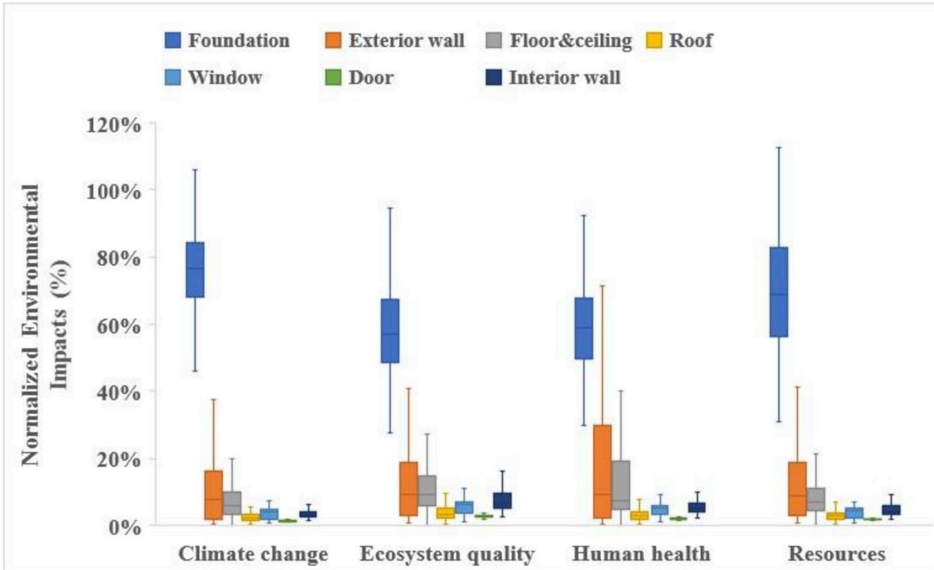

Fig. 6. LCA results comparison between different assemblies in the material production stage normalize by production median.

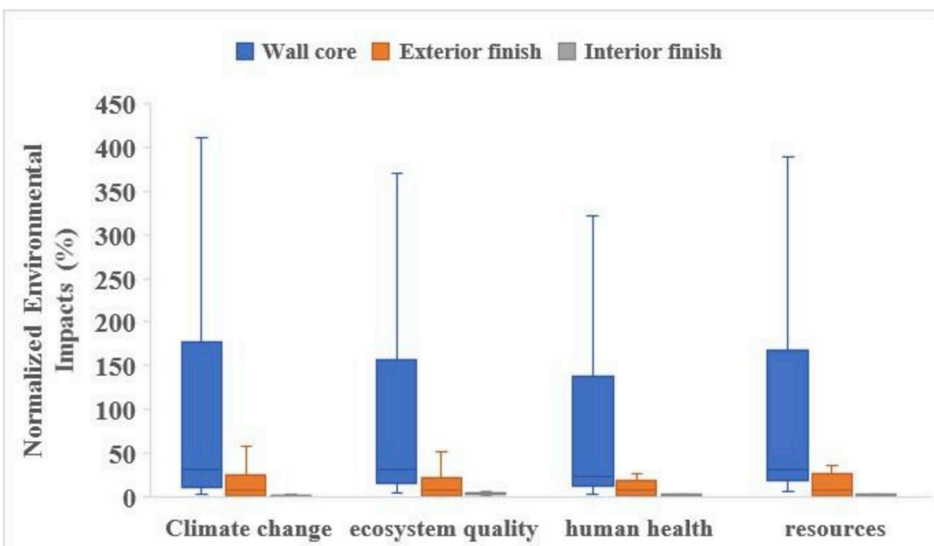

Fig. 7. LCA results comparison between exterior wall layers, including wall core, exterior finish, and interior finish normalize by exterior wall median.

different assemblies in the material production stage are also represented in Fig. 6. The LOD 300 trend for different assemblies is similar to the LOD 100 results.

Here, we note that the use of LCA in the earlier design stage could help building designers estimate the environmental impacts of their designs in the LOD 100 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. For example, determining the best options for wall layers from environmental perspective would be helpful for active players in building industry to easily choose these materials and to help using them more than other options. For the time being, LCA practitioners must use the functional database developed as part of this project manually. Still, the database aims to feed a tool that will make it possible to conduct life cycle assessment directly in BIM at any LOD level automatically and thus better inform all decision makers who use BIM of the environmental consequences of their choices in real time.

4. 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

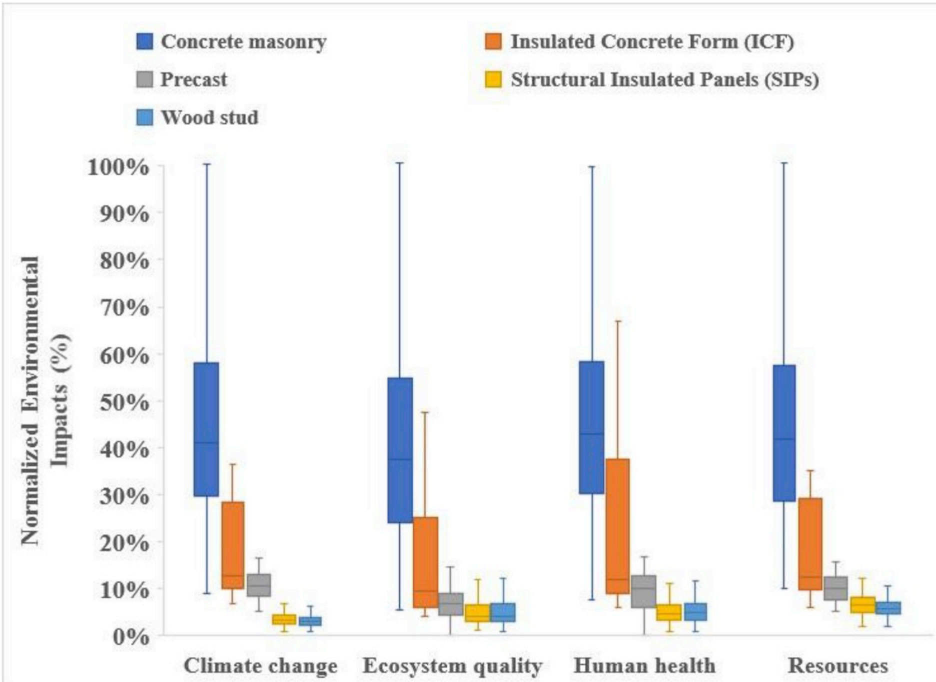

Fig. 8. Comparative LCA results for different wall core options in the LOD100.

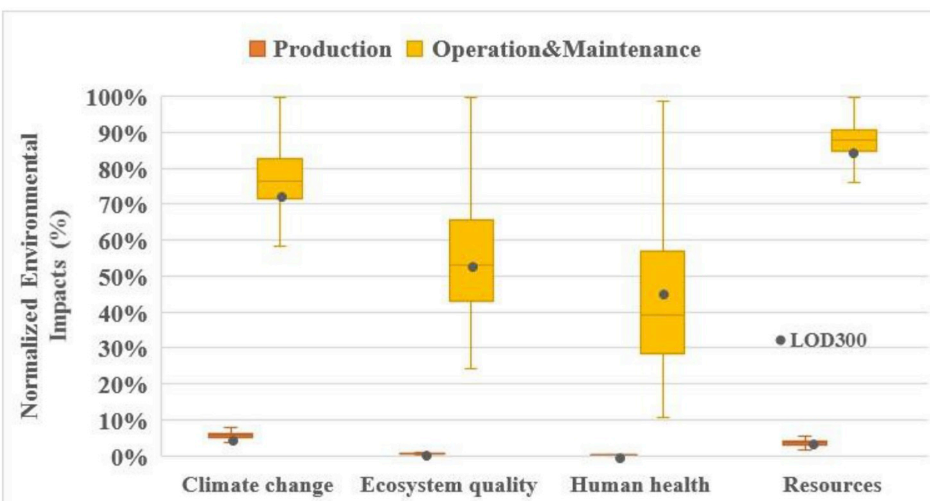

Fig. 9. Comparison of the LCA results for the LOD100 and LOD300 phases.

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.

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