BIM-Based LCA Integration by Evaluating The Environmental Impacts of Whole Building At The Early Design Stage

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Abstract: Recently, environmental Life Cycle Assessment (LCA) has become an impartible part of many building projects. There is greater need to integrate LCA tools with the building design workflow. There are several LCA tools, where some of them use an internal database and some are open source platforms that better enable the use of wide-array of database sources as their life cycle inventory. The former tools have limitations in their database coverage while the latter mostly use the datasets that are not specified for construction projects. This study aims to support the design of resource- and energy-efficient buildings using an integrated LCA methodology in the early design stage. The research aims to integrate LCA capabilities directly into a Building Information Model (BIM) and increase the environmental relevance and scientific robustness of LCA indicators. The plugin, which is developed in the BIM tool is represented to use Ecoinvent to build a complete process of a construction projects to be imported in OpenLCA. The results show much efficiency in using the developed plugin to assist users to find the correct materials from database within the seconds as well as a clear framework that helps to map all the processes of LCA without faults or forgotten processes.

Keywords: Life Cycle Assessment (LCA), Building Information Modeling (BIM), Environmental impacts, Embodied Carbon, Building Performance.

1 INTRODUCTION

It is recognized that climate change is now a major problem facing humanity (Huisingh et al., 2015). Governments around the world have struggled to balance economic growth with its negative effects on the environment, in both the developed and developing world. Buildings, through their construction, operation and eventual demolition, and currently this is associated with large emissions of fossil carbon (Alwan et al., 2015). Sustainable development is a more established concept with a much larger scope compared to that of climate change. It is generally acknowledged that sustainable development can be achieved through balancing the three bottom lines (TBL): society, the environment and the economy (Kang, 2015). Buildings consume energy and contribute to GHG emissions both directly and indirectly throughout their life cycle phases. Direct energy use and emissions are related to the processes of construction, operation, renovation and demolition, whereas indirect energy consumption and associated emissions are caused by production and transportation of materials, as well as technical installations (Huang et al., 2017).

The building and construction industry has been driven to adopt green building strategies in light of increasing sustainability concerns such as reducing CO2 emission and energy dependency on fossil fuels (Lu et al., 2017). As a revolutionary technology and process, Building Information Modeling (BIM) has been regarded by many as a significant opportunity in the architecture, engineering and construction (AEC) industry. BIM emerged as a solution to facilitate the integration and management of information throughout the building life cycle (Wong & Zhou, 2015). There are several tools and methods to help the implementation of sustainable development into the built environment (Alwan et al., 2015; Kang, 2015).

Life cycle assessment (LCA) is a powerful tool to help sustainable design move towards a performance basis. An analytical method for estimating lifetime environmental impacts due to a product or process, LCA can help building designers quantify and validate their sustainability decisions. LCA quantifies the resource consumption and emissions due to constructing, using and disposing of a building, and then estimates the resulting impacts to the environment (O'Connor and Bowick, 2014).

LCA is a useful tool for estimating the cradle-to-grave (i.e. life cycle) impacts of a building. Despite the goal of LCA in evaluating key requirements of sustainability in the building construction industry, there are different challenges facing the application of LCA. Examples of these challenges are the potential changes in the form and function of buildings during the entire service life which typically spans more than 50 years, the challenges of forecasting the whole life cycle and reducing the environmental loads of buildings (Khasreen et al., 2009).

The objectives of this study are to follow the modelling principles of LCA in an integrated and dynamic system to the design environment and to increase the robustness and realism in the environmental evaluation of buildings by integrating BIM principals with embodied carbon impacts analysis through LCA. The focus in this study is to support the design of resource- and energy-efficient buildings using a sound BIM and LCA methodology in the preliminary design stage. A procedure that can be implemented in day-to-day engineering practice for a detailed understanding of building performance is presented. The novelty of the work proposed here is to integrate operational energy analysis in an LCA approach for buildings. The proposed methodology is applied to an archetype office building as a case study project to prepare the integrated BIM-LCA environment to quantify operational and embodied impacts. The case study results and discussion are followed, and finally, concluding remarks are provided.

2 Literature Review

There are various studies about the potential of BIM- LCA integration towards the reduction of environmental impacts in the building sector. Ajayi et al. (2015) recognized the complexity and time-consuming nature of compiling input data during the LCI, and they also pointed out that it limits LCA application in the building sector. They recognized the effect of material specification on the life cycle environmental impact of buildings with the aid of BIM-enhanced LCA methodology. The development of the physical model provides manageable elements by designers from the early stages of design that are defined in the BIM modeling. In that sense, the level of development of the physical model (BIM modeling) defines the level of detail that will be developed through the LCA application. Their developed model was based on a LOD 200 model to obtain the approximate quantities, size, shape, location, and orientation that were required for both energy analysis and quantitative estimates. They have assumed a school building as the functional unit to develop the LCA and they developed a comparative analysis of environmental impacts including all life cycle stages. However, recycling and reuse potential stages were not included in the case studies. They carried out a method combining Revit, GBS, Microsoft Excel spreadsheets and the ATHENA Impact Estimator. While some studies use generic databases, they used regional databases. They used Autodesk Revit to develop the BIM model and then used an Excel spreadsheet to determine the materials that contributed to each of the components (Ajayi et al., 2015).

Kreiner et al. (2015) developed a methodology for building environmental assessment based on LCA, acknowledged the integration of LCA in BIM as a way of improving sustainability performance of buildings. Ilhan and Yaman (2016) presented a framework for this integration in order to build environmental assessment processes in the BIM platform, which would help the provision of documentation for green building certification. The authors state that the shifting approach to the building design, construction and maintenance needs an interdisciplinary collaboration. BIM for integrated sustainable design would simplify the certification process in terms of time and cost due to early stage interactions. Oti et al. (2016) mentioned that integrating sustainability decision modelling into BIM is still at the initial stage.

Despite the fact that the integration of BIM-LCA can reduce time and improve the application environmental performance of buildings from the early stages of design, certain methodological challenges are detected in theoretical terms (Soust-Verdaguer et al., 2017). Several papers which analyzed the integration from a methodological point of view highlighted the software integration as one of the most important challenges (Antón & Díaz, 2014). They assumed that a separate software solution connected to BIM would be easy to implement and user-friendly. Jalaei and Jrade (2014) evaluated and compared the capabilities of different file formats in transferring information from a BIM tool into energy analysis and simulation applications.

Mohammad Najjar et al. (2017) analyzed the methodology of LCA from a building perspective and presented the role of BIM and LCA integration in evaluating the environmental impacts of building materials in order to enable both the decision-making process and sustainable design procedure in the construction sector. The objective of their work was to motivate the integration of BIM and LCA methodologies in an initial design phase and to present the ability of such integration in evaluating the environmental impacts of construction materials. They have used Autodesk Revit as a BIM program and Green Building Studio and Tally applications in Revit as tools to achieve the objectives. Their work provides a practical application of BIM-LCA integration and analyzed the environmental impacts of building materials in the construction sector. They have applied the methodological framework of LCA based on ISO 14040 and 14044 guidelines, taking into consideration the basic steps of LCA methodology.

Although there are several recent works which performed BIM-LCA integration, one gap in the field of BIM and LCA integration lies in the insufficient methodological details to define the framework of BIM and LCA systematically to support the decision-making process in the construction sector and to protect the built environment (Najjar et al., 2017). Rúben Santos and António Aguiar Costa (2016) used a pilot case study in their research, aiming to recognise the influence of designers' decisions on the environmental impact of the building when comparing the environmental impact and energy consumption of a multi-family house with a single family house. As such, the Autodesk Revit was used to build the BIM model, Revit Energy Analysis for energy analysis and Tally for environmental assessment of the buildings. Despite recognizing Revit elements present in the project, the LCA plug-in used in their research did not recognize the objects' information, as it interacted with GaBi's databases. (GaBi, 2019).

3 METHODOLOGY

3.1 Framework and system boundary

The proposed model aims to automate the evaluation of life cycle assessment of a building project from a cradle-to-grave perspective. An integrated BIM-LCA methodology is proposed as the main strategy. Currently, there are several software to conduct LCA and each of them support their own database. The important point is that a precise LCA evaluation depends on the database, impact assessment and a correct model of inputs and outputs. For the first part, the ecoinvent v3.3 database (Ecoinvent 3.3, 2016) was selected as the main database and openLCA 1.9 (Greendelta, 2019) was selected as the engine for LCA calculations.

A plugin was developed to connect BIM software (i.e. Autodesk Revit) to the ecoinvent database which encompasses the integration point between bill of materials and life cycle inventory model for undertaking LCA in the openLCA software. To develop a correct input-output model, first a framework must be developed that contains four main phases of building material production, construction, use (operation and maintenance) and end of life in an LCA model of a project based on EN 15804 (BRE, 2013). System boundaries were defined to determine the inputs and outputs in each life cycle phase. The developed framework and system boundaries considered in this study are shown in figure 1 where the product phase follows the definitions that are defined in ISO 15804 (i.e. raw material supply, transport and manufacturing). In the construction stage, there is a construction process phase, which has been divided into three part of construction activities (i.e. excavation of footing), machine operations at construction site such as tower cranes and related labor-hour work requirements for each sub-task. In the use stage, building element-specific replacement requirements are considered and the inputs from the repair and refurbishment are not included due to lack of information. Demolition activities involving the disposal of materials as well as the transportation of disposed materials off-site were also included in the LCI model. The methodology automates the integration process between the BOM and LCI requirements by customizing and using the application programming interface (API) of a BIM tool (Revit) to enable users to connect their design with different modules instantly from within the BIM tool environment.

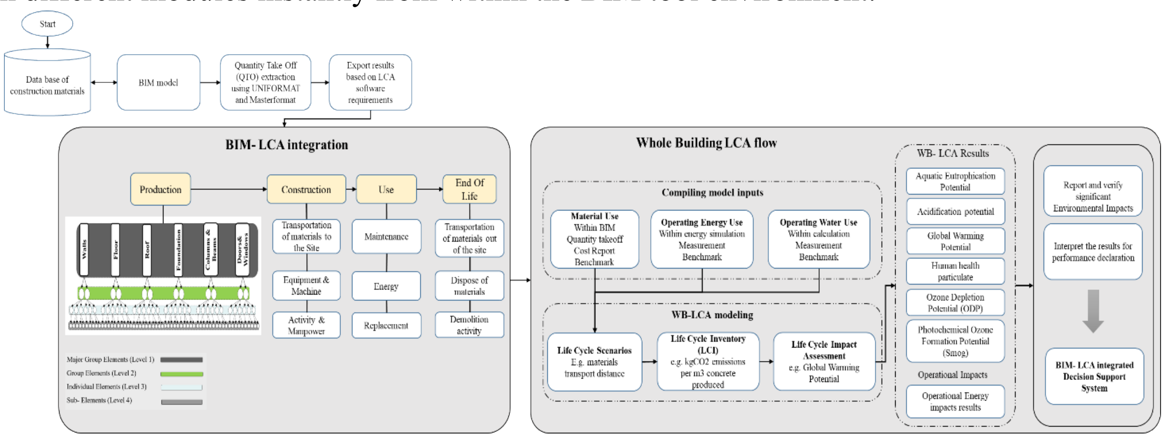

Fig.1. the integrated BIM-LCA model architecture

4 Case study

A sample study of LCA analysis using BIM is done on a 2-story clinic office building in city of Toronto with a total gross area of 1005.35 m2 and 781.91 m2 net conditioned area. Table 1 shows the specifications of the case project as well as the construction type information. The cooling system for the office building is assumed to be electric input ratio (EIR) chiller. The chiller component can be selected at the building level when the main HVAC system type is Variable Air Volume (VAV) or if one or more zone in the model has a fan coil unit. A hot water boiler is used as the heating system for the natural gas scenario. The power is generated in hot water by boiler systems. The generated heat passes through radiators or other devices in rooms throughout the building. To be reheated, the cooler water is required to be returned to the boiler. Generally, natural gas or heating oil is used by boilers. Boilers also use pump in order to circulate hot water through pipes to radiators. An electric heating coil is assumed as a heating system for the electric only scenario of the office building. A coil is a heating device that is connected to the heater itself which transfers the electric energy into heat energy. The heater generates the electric current that flows into the coil.

Table 1: Description of the Case example clinic office building

HVAC*: Heating, ventilation, and air conditioning, VAV*: Variable Air Volume, IEAD*: Insulation Entirely Above Deck.

Office building characteristics	
Parameter	value
Total Building Area [m2]	1005.35
Net Conditioned Building Area [m2]	781.91
Unconditioned Building Area [m2]	223.44
Gross Roof Area [m2]	537.38
Window Opening Area [m2]	102.41
Gross Window-Wall Ratio [%]	17.76
HVAC Air Loops [count]	4
Conditioned Zones [count]	36
Unconditioned Zones [count]	21
Air Terminal	Single Duct: VAV: No Reheat
ZONE HVAC	Baseboard connective electric
Air Loop HVAC	Thermo pump
Electricity + Gas Scenario	Heating: Boiler: Hot Water
	Cooling: Electric EIR chiller
Electricity only Scenario	Heating: Electric heating coil
	Cooling: Electric EIR chiller
Construction information ASHRAE 90.1-2010 exterior wall steel frame ASHRAE 90.1-2010 exterior roof IEAD Exterior slab carpet 8in 189.1-2009 exterior window	

90.1-2010 exterior window metal 189.1-2009 Non-residential skylight without Curb 189.1-2009 exterior door

4.1 Model implementation

Two Input Data Files (IDF) were developed for the office building: one representing natural gas heating and another representing electricity-based heating. These IDF files were based on the American Standard Code for Information Interchange (ASCII) standard (EnergyPlus 9.2, 2019), which contain the data describing the building and HVAC system to be simulated. One issue with the current energy simulation tools, which have the capability to create IDF files is that they do not have the capability of reading the weather (i.e. epw) files based on the projected data. Some tools have an integrated weather files into the software that could not be modified by user to import the customized projected weather data. Among these tools, Honeybee (Honeybee, 2019) is selected, which is a free and open source plugin to connect design tools such as Revit and Grasshopper3D to EnergyPlus, Radiance, Daysim and OpenStudio for building energy and daylighting simulation.

Honeybee is one of the most comprehensive plugins presently available for environmental design since it serves as an object-oriented API for these engines. It accomplishes the energy analysis task by linking the EnergyPlus simulation engine to CAD and visual scripting interfaces of Dynamo/Revit plugins, which is considered to be an ideal parametric tool for this research in order to create IDF files in an integrated BIM-based environment based on the projected weather files. Figure 2 shows the snapshots on the workflow which has been done in the Honeybee tool for creating an accurate building energy model. The zones are defined based on the clinic office usage then the custom loads are assigned, and schedules are set. By assigning the interior zones as well as the openings, the construction specifications are assigned based on the details explained in table 1. The HVAC system is defined for each building design scenario. The customized projected weather files (.epw) were imported to the energy plus panel. As illustrated in figure 2, by defining the file name and by switching the boolean toggle to true, the writing IDF process is started.

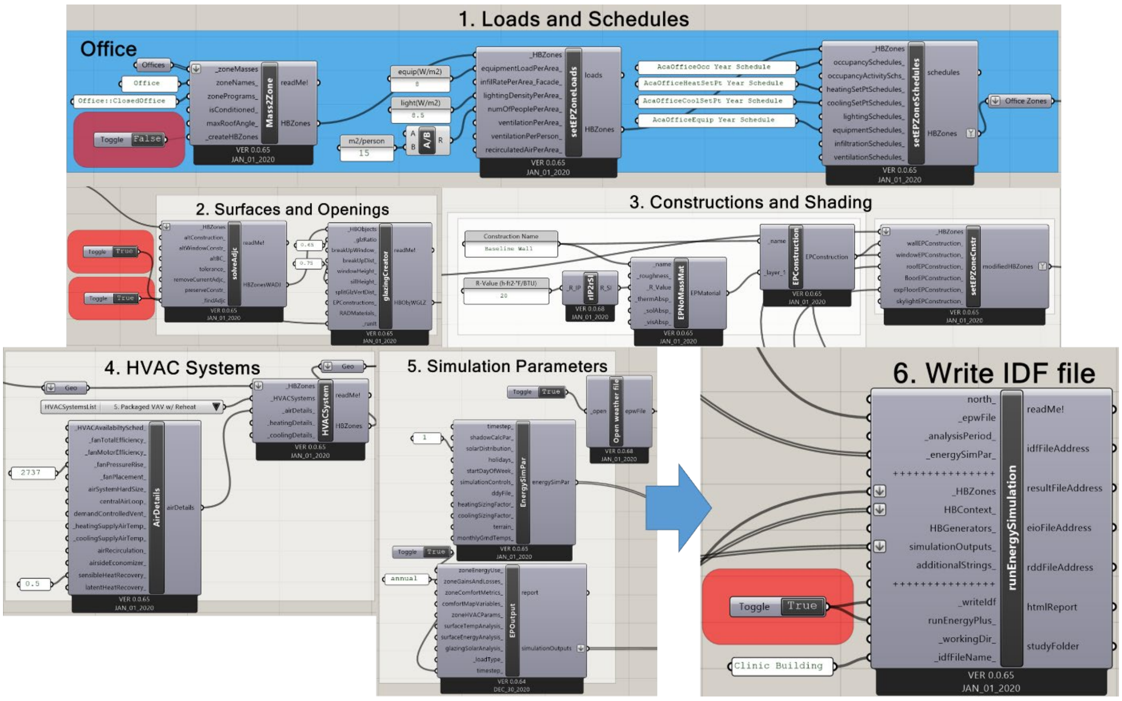

Fig.2. the process of creating IDF files in Honeybee for the office building based on the electricity mix scenarios

4.2 Calculation of operational impacts

The whole building energy simulation program utilized was EnergyPlus (EnergyPlus 9.2, 2019) , as it is a widely used program that engineers, architects, and researchers use to model both energy consumption— for heating, cooling, ventilation, lighting and plug and process loads—and water use in buildings.

The environmental impact assessment model to calculate the life cycle environmental impacts was based on the TRACI method (LCIA methods, 2015), which is commonly used for North America.

In the developed BIM-LCA plug-in, as shown in figure 3, through selecting the building lifespan to be 60 years as well accounting for regional specifications, key building attributes were specified. The production stage includes the data mapping between the materials quantity take-offs extracted from the BIM model with the inventory list where the ecoinvent v3.3 database was used in a Revit plugin. The plug-in shows all the extracted materials in a hierarchical format (see figure 3). Therefore, the user can track and manage data mapping to ensure all the materials used in the project have been modeled and considered in the LCA. By selecting each item, the list of all relevant gate-to-gate processes in ecoinvent are shown and the user selects the most appropriate products/activities. To save time, the ecoinvent database is pre-filtered in the plug-in which enables a short list of appropriate materials/activities for the user to select from. The plugin takes the quantify take off from the BIM model and indicates the mapped items with colour coding (mapped items in green, incomplete mapping in yellow, not mapped items in gray).

For the construction phase the plugin offers three tabs where first all the materials used and associated transportation requirements across each building element were specified. The distance between manufacturing (or regional storage) and construction site can be automatically calculated by area code (e.g. zip code) via a google map feature. In this study the distance of 100 km was assumed for the transportation. The building construction process includes the quantification of installation and excavation energy and the amount of building material waste generated on site. The next tab is related to the machines and equipment used in the construction projects (e.g. hydraulic loader or crane). Since construction equipment are used on an hourly basis, they are assigned to the whole building process. The construction design and excavation activities require both fossil fuels and electricity. Due to a lack of specific case study data, mean electricity and diesel values required for construction of 60 MJ and 15 MJ per m2 of building area, respectively (Rezaei et al., 2019) were utilized. Wasted material generation were considered based on common waste factors (Athena, 2019) of the structural materials (i.e. concrete, steel, gypsum etc.) which are assumed to be transported to a waste sorting facility with an assumed distance of 100 km.

Embodied impacts also occur during the use phase of the building due to replacement and maintenance of building elements during the whole building life cycle. Material replacement is included in the maintenance phase on the basis of each material's service life. The list of elements that are extracted from the BIM model are displayed in the plugin and the user can define element-wise life expectancies. In this study default life expectancies (usage) for each building element were assumed (Athena, 2019). For the clinic building, painting was assumed to be performed every 5 years and doors, windows and curtain walls were assumed to be replaced every 20 years while the insulation and structural components were assumed to remain for the entire life cycle of the building.

The end of life stage includes an activity section similar to construction stage. The electricity at the demolition stage is the fossil fuel needed to power the deconstruction machines in the building. The end user can also select whether each building element should be disposed or recycled and thus link to an appropriate ecoinvent activity. The material disposal stage is modeled based on the building assembly classification (UNIformat). The demolished material was assumed to be transported from the building site to a landfill or waste sorting facility, and in this study, a distance of 100 km distance was assumed.

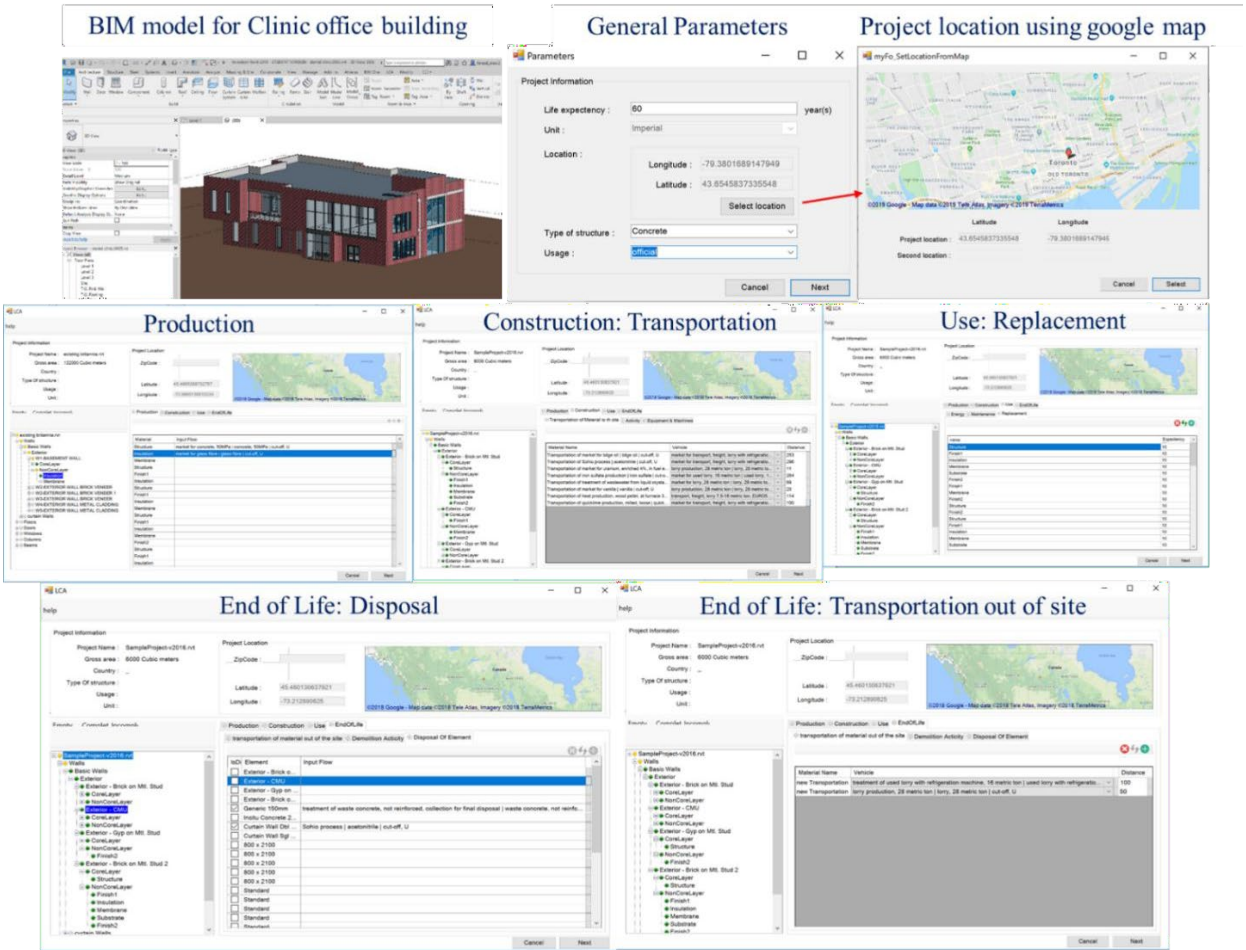

Fig.3. The process of linking material quantity take-offs with the LCI database using the BIM-LCA Revit plug-in

The output of the plug-in results in a JSON file equivalent to the OpenLCA schema (Greendelta, 2019) which is then imported into the OpenLCA software where LCA calculations can be performed. Based on the TRACI environmental impact method, the LCA calculations were performed where Monte Carlo-based uncertainty analysis with 5000 iterations was also undertaken.

Figure 4 shows the deterministic contribution percentages of embodied carbon based on the sub-categories of the clinic building life cycle (i.e. production, construction, replacement and end of life) as well as the normalized GWP impacts per square meter of conditioned area. As it is demonstrated, production has the highest share in the embodied impacts followed by the replacing the building components at the use stage. Floors and walls showed the largest percentage in GWP impacts at the production stage around 16% and 13%, respectively.

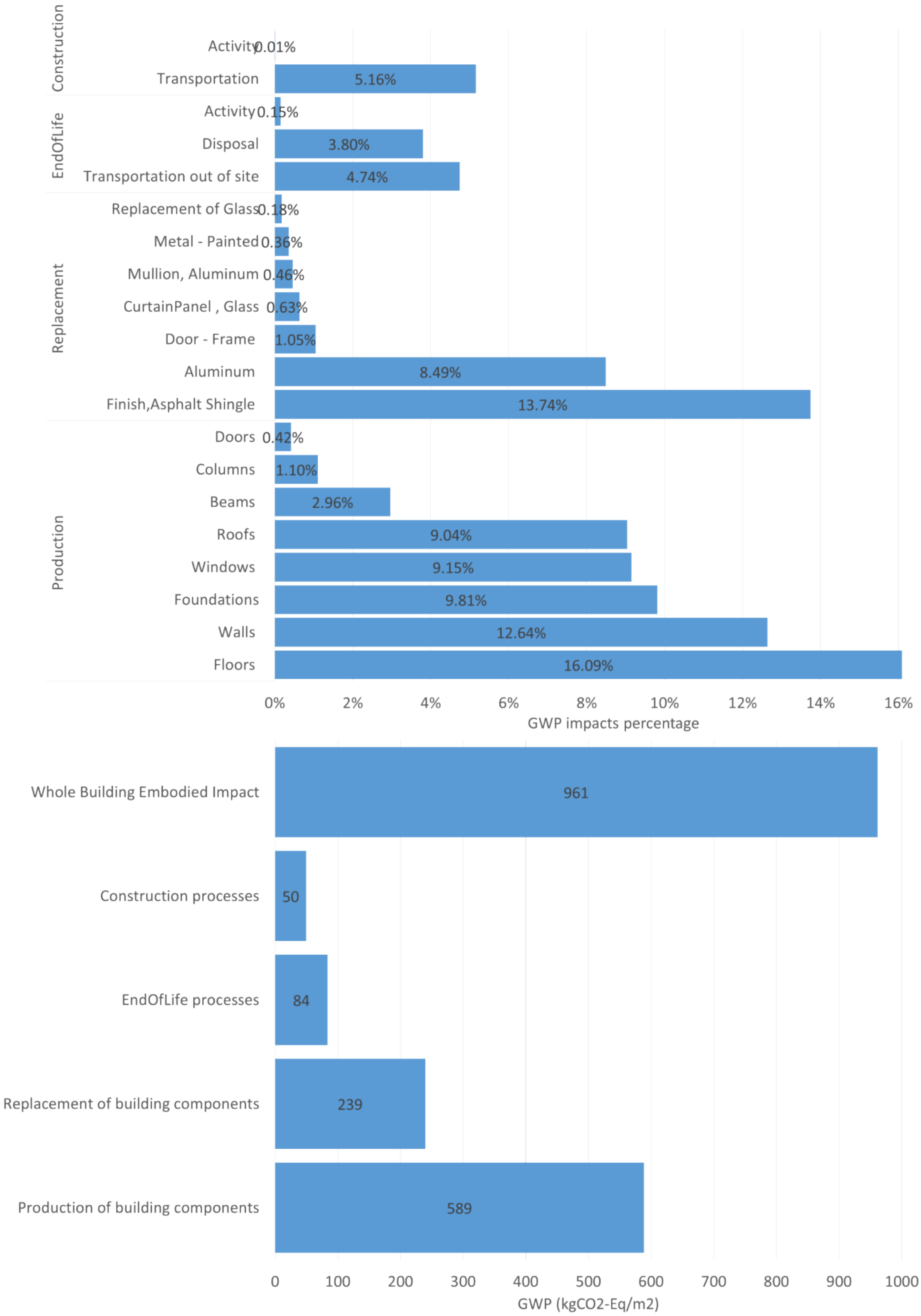

Fig.4. Global Warming Potential (GWP) embodied impacts contribution tree for the office building

These results are compared and validated with the embodied impacts benchmarking study (CLF, 2017), which evaluates the embodied GWP per square meter of building area based on the S=Structure, SF=Structure/Foundation, SFE=Structure/Foundation/Enclosure and SFEI=Structure/Foundation/Enclosure/Interiors for almost 1000 buildings, as shown in figure 8. By assuming the conditioned area of the building (781.91 m2), the embodied carbon for the studied office building resulted in 898 kgCO2eq/m2, which is in an acceptable area for SFEI benchmark. Figure 5 also illustrates the Monte-Carlo analysis results for about 5000 runs of the embodied carbon analysis through OpenLCA. Although the gross floor area is a common functional unit, but it is preferable to use net floor area as a functional unit because it is describing space that can be occupied for the operational purposes of the building. Using the net floor area was therefore the approach used here.

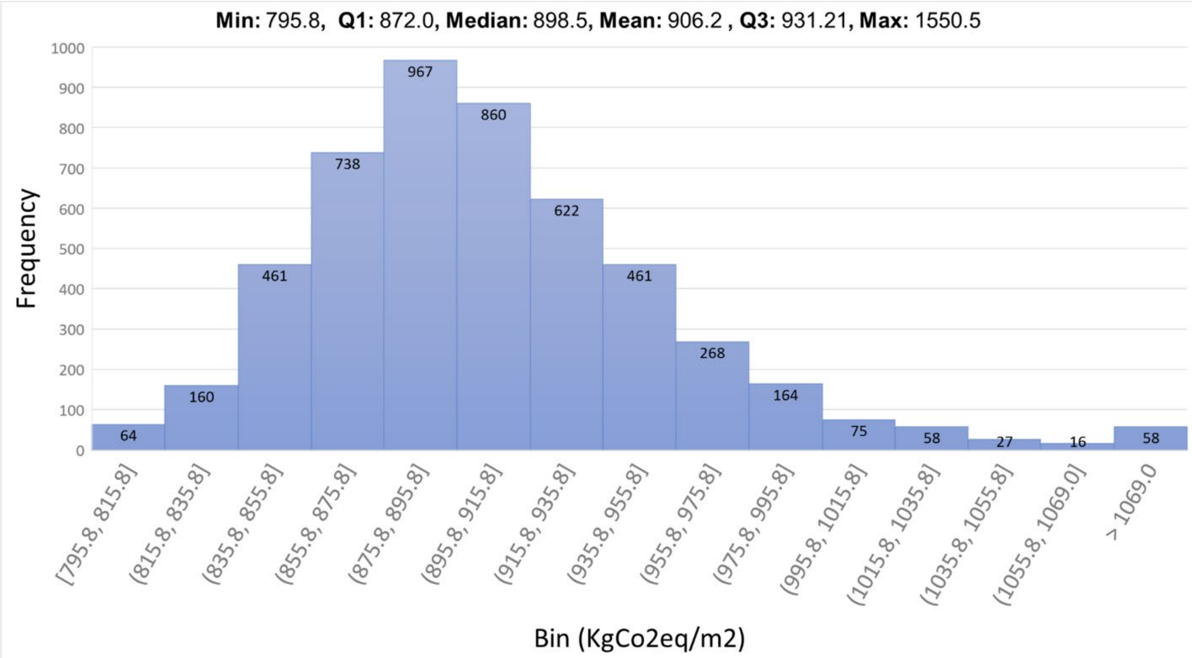

Fig.5. the Mont-Carlo analysis results for the embodied carbon for the clinic office building (5000 runs)

Figure 6 shows the whole-building GWP results where both the operational and embodied impacts are presented for the office building. The result is represented in kg CO2eq/m2 for both the natural gas and electricity heating alternatives. The evaluation results are clearly favourable for electricity-based heating for the office. The proposed approach would assist the design team to evaluate building environmental performance during its lifecycle in more accurate, close to realistic and more efficient way (less total GWP impacts). Therefore, the electricity-based space and water heating is recommended as a climate friendlier HVAC system for the case study office building in Ontario.

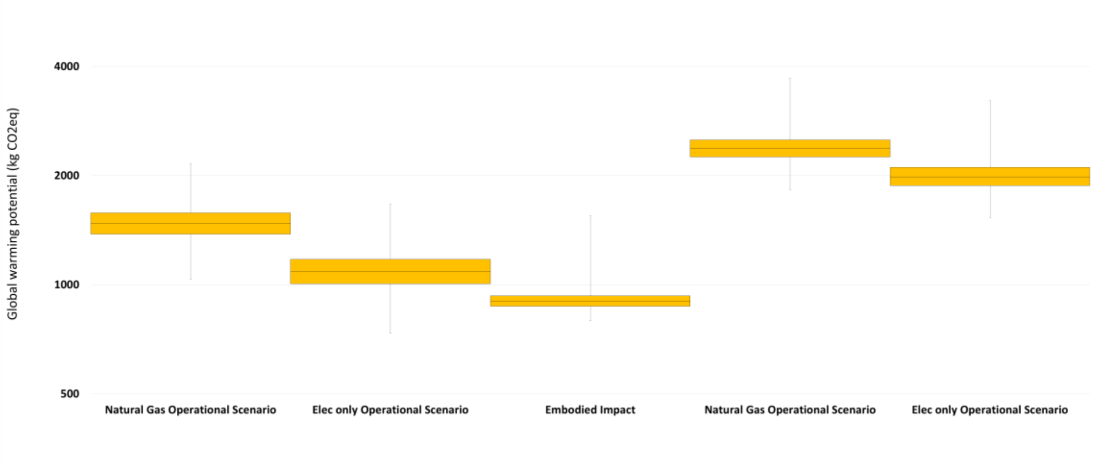

Fig.6. the total GWP results of the office building.

5 Conclusion, limitations and recommendations

The intent of this study was to provide a framework for design teams to generate more accurate and realistic environmental impact analysis in order to have a better idea about the building project while making important decisions at the conceptual stage. The novelty highlighted in this paper describes the model's different modules, which are integrated into each other based on an semi-/automated process by creating new BIM-LCA plug-in and improving the functionality of the existing tools so that users will be able to start the sustainable design of a proposed building project at the conceptual stage of its life cycle in a timely and cost-effective way. Using a BIM integrated platform moves the design decisions forward at the early stage especially when comparing different design alternatives, which is considered to be an attribute of this research.

There were several simplified assumptions in the proposed sample model which can be considered as important modelling limitations. In conducting the embodied impact analysis, there were several data gaps between the bills of materials with the available unit processes in the LCI database. The construction and maintenance activities were excluded from the embodied impacts assessment due to the lack of available data. The transportation distances to transport materials to site were assumed as a constant number (100km) during the building life cycle. The embodied impacts were assumed to be constant due to the lack of more detailed region-specific LCI data and whether these requirements should be changed through the life cycle of the project based on the climate change scenarios.

The creation of IDF files for energy analysis through Honeybee was done in a semi-automatic way since the identification of zones, spaces, construction, HVAC and schedules were required to be done by the user. To fully automate this process, this process could be integrated in the BIM-LCA interfaces. It is recommended that the proposed method is implemented in more case building from various types (i.e. low-rise, mid-rise and high-rise), various occupation types (i.e. residential, office, commercial) and various structural types (i.e. concrete, steel, wood) to be able to come up with more comparable and accurate analysis results in order to develop a climate change and grid mix decision support system at the early design stage.

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