SUST, 2024, 4(1): 000034

Sustainable Structures
ISSN: 2789-3111 (Print); ISSN: 2789-312X (Online)
http://www.sustain-dpl.com/journal/sust
DOI: 10.54113/j.sust.2024.000034

CASE REPORT

Comparison of using two LCA software programs to assess the environmental impacts of two institutional buildings

Chang Gu[a], Homgmei Gu[b], Meng Gong[a,*], Janet Blackadar[a], and Nadia Zahabi[a]

[a] University of New Brunswick, 28 Dineen Drive, Fredericton, E3B5A3, Canada.
[b] Forest Products Laboratory, One Gifford Pinchot Drive, Madison, 53726, United States.
[*]Corresponding Author: Meng Gong. Email: mgong@unb.ca.

Abstract: The current trends in climate change have captured the attention of stakeholders across multiple industries, including the building sector. With the introduction of innovative building materials such as mass timber products (MTPs), it has become essential to evaluate their environmental performance. In response, a variety of life cycle assessment (LCA) software programs are available to meet this need. However, it is crucial to understand how different LCA software and databases might influence the results. This study was aimed at exploring the impact of two widely used LCA software programs, SimaPro and Athena Impact Estimator, on LCA results. Two buildings were employed to conduct this study, a traditional institutional building and a mass timber building currently under construction. By comparing the numerical outputs from both software programs, it was discovered that while both could reach similar conclusions regarding the environmental impacts of a building, their use is limited to comparative purposes only. The software programs produced distinct numerical values in their outputs and attributed the sources of impacts differently, indicating they cannot be used interchangeably. However, either SimaPro or Athena Impact Estimator was suitable for estimating the global warming potential of a building during stages A1 to A3.

Keywords: Life cycle assessment software programs; environmental impacts; mass timber products; mass timber building; institutional buildings

1 Introduction

Climate change caused by human activities has already happened with observable change in temperature and precipitation [1]. With the construction industry being one of the responsible sectors for causing heavy carbon emissions and degradation of natural environment, green building standards were created by the authorities and organizations to reduce the environmental impact caused by the construction industry [2]. One of the methods for lowering construction impact on climate change is choosing green building materials, such as mass timber products (MTPs). MTPs are a term used for defining a category of engineered wood products with large section and size that has the potential to replace traditional construction products like structural steel and reinforced concrete [3]. These products include panel products that come in large thickness, length, and width, which are usually manufactured by combining lumber with mechanical connectors or adhesives, such as cross-laminated timber (CLT), glue-laminated timber (GLT), nail-laminated timber (NLT), and dowel-laminated timber (DLT) [4]. Application of these products for construction has multiple advantages over steel and concretes, including but not limited to less construction time on site, improved performance in thermal insulation,

Received: 24 December 2023; Received in revised form: 4 May 2024; Accepted: 8 May 2024

reduction in weight of the structure, and reduction in carbon footprint when lumber is sourced from sustainably managed forests [5]. Wood also has the ability to store carbon in the materials as trees absorb carbon dioxide through photosynthesis when they grow, and this carbon remains stored in wood products during their service life [6]. This means a mass timber building can be considered as a carbon sink in the service life of the building. This may help mitigate urgent climate change as the buildings will continue to keep the carbon until the end of the building service time [7], which are assumed to be 50~60 years [8, 9].

However, the benefits of buildings constructed with MTP need to be quantified. To quantify the total environmental impact of a building, it is necessary to conduct the life cycle assessment (LCA) on a whole building scale. LCA is a common method for addressing environmental aspects and potential environmental impacts of a product throughout its life cycle, including all processes from raw material acquisition through production, use, end-of-life process, and recycling [10, 11, 12]. The system boundary of a LCA study identifies which stages or aspects of a product life cycle should be included in the study. A previous review report [13] summarized that there are three types of tools/programs used for LCA studies. For LCA of generic products, the first type is utilized, including GaBi, SimaPro, and OpenLCA. The second type is streamlined tools for assessing the whole building, containing Eco-Quantum, Athena Impact Estimator (Athena IE), Tally, OneClick LCA, and eTool. The third type consists of the frameworks for assessing whole building, such as BREEAM [14] and LEED [15].

Using LCA as a tool to compare the environmental performance of buildings is becoming an important practice. Many comparative LCA studies showed that buildings constructed with MTPs usually had lower global warming potentials (GWP) [16-20]. But when it comes to decision-making, stakeholders would like to know the specific values of environmental benefits when applying MTPs as building materials in their cases. In ideal situations, comparing the LCA results of the planned mass timber building to other existing buildings that have similar characteristics (such as building profiles, height, and usage pattern) or comparing the LCA result of the planned mass timber building to a concrete/steel version of the building would be helpful with the decision-making process. However, buildings came in different shapes, sizes, and different usage patterns. It’s not easy to find an existing building with similar characteristics that have an LCA report. Given this challenge, the focus of this study was shifted towards the necessity of identifying the specific sources of environmental impacts on building’s major structural components, offering valuable insights for decision-making in the absence of direct comparable case studies.

Use of different LCA software and associated databases in the LCA assessment would produce different results. Hemmati et al [21] conducted a LCA study on the transportation stage of CLT panels from three different sources to a construction site located at Fayetteville, Arkansas, USA. The two software programs that contain different databases (SimaPro with Ecoinvent database and Tally with Gabi database) were used to examine the discrepancies in GWP results. Their findings indicated that utilizing various software programs and database combinations caused various output values ranging from 23% to 61%. Hemmati et al mentioned that this difference was caused primarily by the two databases used, with different characterization factors. Another possible reason was that the Tally LCA tool lacks data that are suitable for the international transportation. Kalverkamp et al [22] compared the LCA results of combustion engine vehicle and electric vehicle modeled with GaBi professional database and Ecoinvent database. Their study also showed that the application of two different databases caused a difference in absolute impact results. They found that, in the case of the impact of the petrol module in both databases, significant differences included 19.7% in climate change impact, 217.1% in human toxicity impact, 59.0% in acidification impact, and 377.3% in water depletion impact.

This study was aimed at studying the difference in LCA results generated by two different LCA tools optimized for the North American market and investigating the environmental impacts of a new mass timber institutional structure under construction and a traditional steel-frame-building on the University of New Brunswick (UNB) campus, Fredericton, Canada. LCA was conducted to quantify the total environmental impacts of these two buildings. This study also examined the difference in LCA results caused by applying different life cycle inventory (LCI) database localized for North American market and using two commonly used LCA software programs, Athena IE with its own LCI database and SimaPro with DATASMART database. These databases contain LCI material data, i.e., the building materials in this case, which were critical to construct the LCA models of the building.

2 Methods

To examine the environmental impacts of institutional buildings built with MTPs, two LCAs were conducted on the newly designed academic building and the existing building on UNB campus, following the international standard ISO 21930 "Sustainability in buildings and civil environmental product declarations of construction products and services" [12] and European standard EN15978 "Sustainability of construction works–Assessment of environmental performance of buildings–Calculation method" [23].

2.1 Scope of LCA

2.1.1 Research Buildings

The first building studied was the extension structure "Engineering Commons" of the Head Hall on the UNB campus in Fredericton, Canada. Head Hall is an institutional building mainly used by the Faculty of Engineering and Faculty of Computer Science at UNB. It was built in 1968 but received expansion to connect it with other existing buildings in 1966, 1989, and 2000. The extension included in this study would be the newest addition to Head Hall. Structural components of this extension include a reinforced concrete foundation, with structural steel columns and beams used as support elements in the basement. Starting from the first floor, all the major structural components, i.e., columns, beams, and floor panels, will be made with CLT panels and GLT columns and beams. The interior walls of this structure will be built with steel frames, sound insulation batts, and two layers of 16mm gypsum boards. The exterior walls of the structure will contain exterior insulation and finish systems (EIFS) and glass curtain walls (**Fig. 1**).

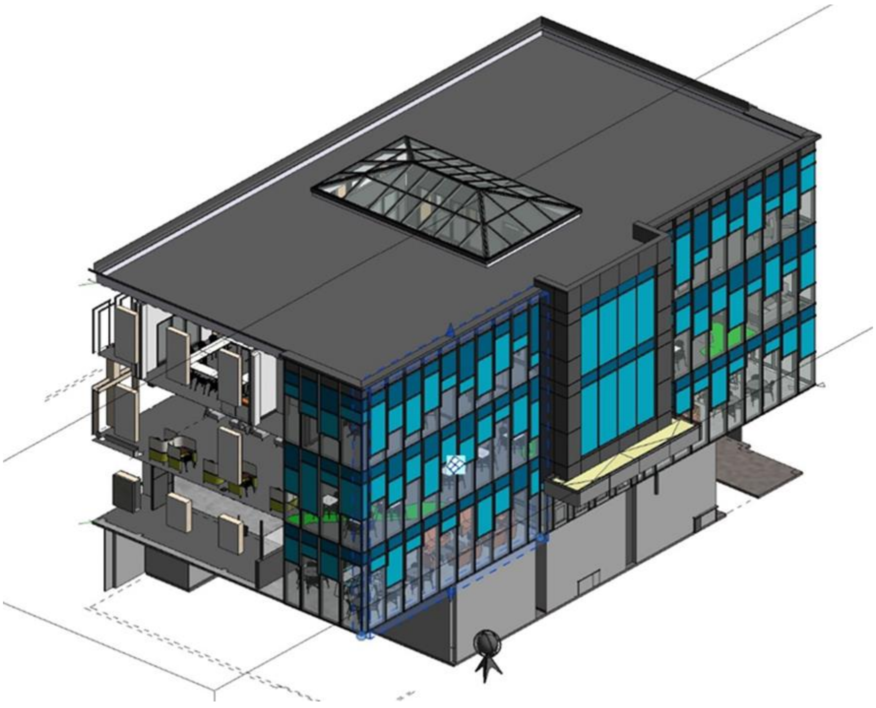

Fig. 1. External view of the Revit model of the Engineering Commons Building (Source: Office of Planning and Operation, the University of New Brunswick, Canada).

Functional spaces of this building include a large atrium featuring glass skylight and large floor opening on the second and the third floor to ensure maximum amount of natural lighting, plus several open study spaces. In the design, a chemical engineering laboratory and a computer laboratory will be in the basement. Three study rooms are planned to be built on the second floor. Six individual offices, two larger shared offices, and one meeting room will be built on the third floor of the structure. A special feature of this building includes an earth tube that will pre-condition air before circulating it in the building. In order to accommodate the earth tube, part of the foundation at the mechanical room area is planned to be built deeper than that structurally required. The earth tube itself will not be included in the study, but materials required for deepened foundation will be considered in the model.

Although this structure is extension of an existing building, the engineers working on this project ensures that the structural parts of this extension are not connected to the existing structure, which means the design of this extension can be used for a standalone building. During the collection of material information, the extra amount of glass curtain wall for this structure will be considered in the bill of each material to ensure a fair comparison between the structures (**Fig. 2**).

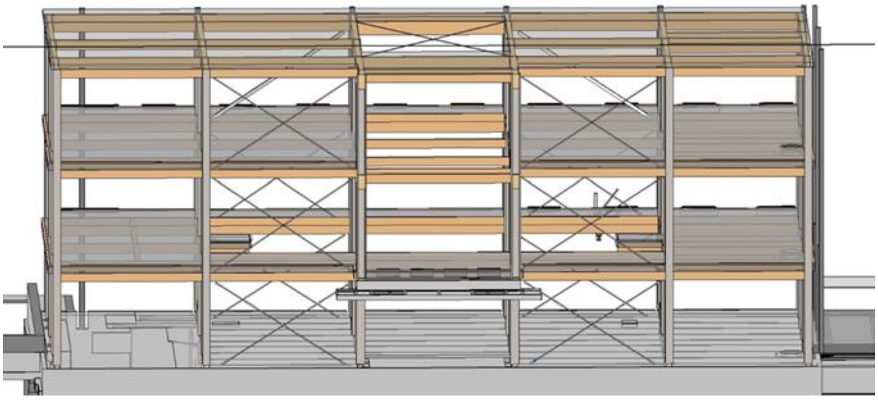

Fig. 2. Mass Timber Frame of the Engineering Commons Building (Source: Office of Planning and Operation, the University of New Brunswick, Canada).

The second building used in this study was IUC New Forestry Building on the same campus as the first building (**Fig. 3**). This building is an institutional building built in 1975 and opened for use in 1976. The structural component of this building includes a foundation built with reinforced concrete and steel framing, and floor panels with reinforced concrete construction. The interior walls of this building were constructed using the concrete masonry units (CMUs). The same material, in addition to a layer of brick and rigid foam insulation, was used to build the external walls. 20 faculty members' individual offices and four graduate student offices comprise the building's functional area. The structure also has two classrooms, and 15 small laboratories and computer rooms. Two greenhouses on the roof and a single cold storage unit in the basement are two of this building's distinctive features, which were not included in the research.

Fig. 3. IUC New Forestry Building on UNB Fredericton Campus.

Considering the IUC New Forestry's outdated blueprint's limited ability to provide relevant data, only the major components of these two buildings were included in this study, including exterior walls, interior partitions, floors, roof, and structural components. However, windows and doors were not considered in this analysis.

This LCA study's functional unit was determined to be a 1-m^2 floor area to ensure a fair comparison as the Engineering Commons Building has a slightly smaller building footprint than the IUC New Forestry Building.

Due to the lack of information on structural steel available in New Brunswick, the alternative design of the Engineering Commons with MTPs replaced with traditional material was not created, therefore, this study could not be treated as a comparative study on environmental advantages of MTPs.

2.1.2 System boundary

Table 1 lists the life cycle stages of a building in the LCA study, which are defined by EN15978 [23]. The system boundary for this building LCA study included the Products Stage of A1-A3 as defined in **Table 1** (a cradle-to-gate LCA study). The carbon sink capability of MTPs used in the first building was quantified in this study but reported separately. Although this capability might have significant impact on carbon footprints of the building, these advantages are not encompassed in A1–A3 stages of the life cycle. It was assumed that the carbon in MTPs would be stored for 60 years of the building's life, after which it would either be released back into the environment or remain in the materials to be recycled into another product. This process helps delay the GHG emissions associated with these building materials.

Table 1. Building life cycle stages defined by EN15978 [23]

Building Assessment Information	Building Lifecycle Information	Product Stage	A1	Raw material supply
			A2	Transport
			A3	Manufacturing
		Construction Process Stage	A4	Transport
			A5	Construction-installation process
		Use Stage	B1	Use
			B2	Maintenance
			B3	Repair
			B4	Replacement
			B5	Refurbishment
			B6	Operational energy use
			B7	Operational water use
		End-of-life Stage	C1	Deconstruction demolition
			C2	Transport
			C3	Waste processing
			C4	Disposal
	Supplement Information Beyond the Building Life Cycle		D	Benefits and loads beyond the system boundary

2.2 Life cycle inventory (LCI) of building materials

One of the initial steps in LCA study is to collect the material and energy data required to accomplish the study's objectives. As per the ISO standard, these data are utilized to create the LCI data of a service or product [12]. The building LCA analysis started with creating the bill of materials (BOM) from a building design, then collecting the LCI data of each product from a LCI database for building materials.

To acquire information for the bill of material, the software known as Revit [24], was used to gather data on building materials and quantities of the Engineering Commons Building from the Revit model provided by engineers working on this building project, which is provided in **Table 2**. The software, namely On-Screen Takeoff [25], was employed to collect building materials and quantity information from the architectural and structural designs of the IUC New Forestry Building as no Revit model was available for this building, which is given in **Table 3**. Information such as the length and height of a wall and area of a floor were acquired from these software programs and calculated with the corresponding material data such as spacing of studs in a wall and density of materials.

Table 2. Bill of Material of the Engineering Commons Building

Assemblies	Material name in Athena IE	Amount	Unit	Material name in LCI database
Column and Beams	Hollow Structural Steel	0.8686	Tonnes	Steel, low-alloyed, at plant/US-EI U
	Rebar, Rod, Light sections	1.1665	Tonnes	Reinforcement steel, at plant/US-EI U
	Bolts, Fasteners, Clips	1.9364	Tonnes	Chromium steel 18/8, at plant/US-EI U
	Wide Flange Sections	21.412	Tonnes	Steel, low-alloyed, at plant/US-EI U
	Glulam Sections	90.3041	m^3	Nordic GLT beam
Floor	Concrete Benchmark CAN 30 Mpa	234.432	m^3	Concrete, sole plate and foundation, at plant/ US* US-EI U
	Cross Laminated Timber	172.6898	m^3	Nordic CLT panel
	Expanded Polystyrene	771.85	Kg	EPS insulation board, at plant/kg/ RNA
	Galvanized Decking	3.939	Tonnes	Galvanized steel sheet, at plant/ RNA
	Rebar, Rod, Light Sections	4.3834	Tonnes	Reinforcing steel, at plant/US- USEI U
Roof	6 mil polyethylene	58.5	kg	Packaging film, LDPE, at plant/US- US- EI U
	Cross Laminated Timber	81.5575	m^3	Nordic CLT panel
	Expanded Polystyrene	849.8133	kg	EPS insulation board, at plant/kg/ RNA
Foundation	Concrete Benchmark CAN 30 MPa	463.953	m^3	Concrete, sole plate and foundation, at plant/ US* US-EI U
	Rebar, Rod, Light Sections	21.0787	Tonnes	Reinforcing steel, at plant/US- USEI U
Wall	The input value for the Athena Impact Estimator is height, length, stud spacing and other info for the walls, therefore there's no direct bill of materials for walls from Athena IE	3163.85	kg	Chromium steel 18/8, at plant/US- US-EI U
		1488.34	kg	Glass wool mat, at plant/US* US-EI U
		3039.129	m^2	Gypsum wallboard product, type X, 0.625 inch (15.875 mm)/m2/RNA
		53.949	m^2	Metal panel, insulated, at plant/m2/RNA
		119	kg	Polystyrene foam slab for perimeter insulation {GLO}/market for/ Conseq, S
		1061.563	m^2	Curtain wall

Two software tools were used in later steps of collecting LCI data and performing impact assessment to conduct a comparison study on the difference of their outputs. SimaPro [26], along with the DATASMART 2021 LCI package [27], was employed to carry out this LCA study. This database offers data on the GWP impacts of individual materials' manufacturing and transportation. DATASMART package include the US LCI database and US-Ecoinvent database [28] to regional electricity data specific to the United States market, but no data customized for Canadian market.

Table 3. Bill of Material of the IUC New Forestry Building

Assemblies	Material name in Athena IE	Amount	Unit	Material name in LCI database
Column and Beams	4” Normal Weight Concrete Block	9660.34	kg	Concrete block, at plant/US**US-EI U
	6” Normal Weight Concrete Block	6057.24	kg	Concrete block, at plant/US**US-EI U
	8” Normal Weight Concrete Block	24714.83	kg	Concrete block, at plant/US**US-EI U
	Expanded Polystyrene	378.87	kg	EPS insulation board, at plant/kg/ RNA
	Hollow Structural Steel	4.62	Tonnes	Steel, low-alloyed, at plant/US- US-EI U
	Ontario (Standard) Brick	82484.46	kg	Brick, at plant/US- US-EI U
	Rebar, Rod, Light Sections	3.52	Tonnes	Reinforcing steel, at plant/US- USEI U
	Small Dimension Softwood Lumber, kiln-dried	4.88	m^3	Sawn lumber, softwood, planed, kiln-dried, at planer, NE-NC/m3/RNA
	Steel Plate	0.02	Tonnes	Reinforcing steel, at plant/US- USEI U
	Wide Flange Sections	133.26	Tonnes	Steel, low-alloyed, at plant/US- US-EI U

Floor	Concrete Benchmark CAN 30 MPa	140.98	m^3	Concrete, sole plate and foundation, at plant/ US* US-EI U
	Galvanized Decking	17.38	Tonnes	Galvanized steel sheet, at plant/ RNA
Wall	12” Normal Weight Concrete Block	11885.25	kg	Concrete block, at plant/US**US-EI U
	4” Normal Weight Concrete Block	53842.65	kg	Concrete block, at plant/US**US-EI U
	6” Normal Weight Concrete Block	455791.88	kg	Concrete block, at plant/US**US-EI U
	8” Normal Weight Concrete Block	204173.62	kg	Concrete block, at plant/US**US-EI U
	Expanded Polystyrene	1591.59	kg	EPS insulation board, at plant/kg/ RNA
	Ontario (Standard) Brick	263963.05	kg	Brick, at plant/US- US-EI U
	Small Dimension Softwood Lumber, kiln-dried	6.78	m^3	Sawn lumber, softwood, planed, kiln-dried, at planer, NE-NC/m3/RNA
Roof	6 mil polyethylene	6.77	kg	Packaging film, LDPE, at plant/US- US-EI U
	6” Normal Weight Concrete Block	13346.86	kg	Concrete block, at plant/US**US-EI U
	8” Normal Weight Concrete Block	75930.77	kg	Concrete block, at plant/US**US-EI U
	Concrete Benchmark CAN 30 MPa	70.34	m^3	Concrete, sole plate and foundation, at plant/ US* US-EI U
	Expanded Polystyrene	1033.91	kg	EPS insulation board, at plant/kg/ RNA
	Galvanized Decking	5392.43	kg	Galvanized steel sheet, at plant/ RNA
	Metal Roof Cladding	1531.28	kg	Galvanized steel sheet, at plant/ RNA
	Ontario (Standard) Brick	93957.26	kg	Brick, at plant/US- US-EI U
	Rebar, Rod, Light Sections	2910	kg	Reinforcing steel, at plant/US- USEI U
	Small Dimension Softwood Lumber, kiln-dried	7.11	m^3	Sawn lumber, softwood, planed, kiln-dried, at planer, NE-NC/m3/RNA
	Softwood Plywood	375	kg	Plywood, at plywood plant, US SE/kg/US
Foundation	4” Normal Weight Concrete Block	20919.69	kg	Concrete block, at plant/US**US-EI U
	Bolts, Fasteners, Clips	0.13	Tonnes	Chromium steel 18/8, at plant/US-EI U
	Concrete Benchmark CAN 30 MPa	447.14	m^3	Concrete, sole plate and foundation, at plant/ US* US-EI U
	Expanded Polystyrene	135.4	kg	EPS insulation board, at plant/kg/ RNA
	Ontario (Standard) Brick	5960.96	kg	Brick, at plant/US- US-EI U
	Rebar, Rod, Light Sections	13.74	Tonnes	Reinforcing steel, at plant/US- USEI U
	Welded Wire Mesh/ Ladder Wire	1.37	Tonnes	Chromium steel 18/8, at plant/US-EI U
	Wire Rod	0.38	Tonnes	Reinforcing steel, at plant/US- USEI U

Two software tools were used in later steps of collecting LCI data and performing impact assessment to conduct a comparison study on the difference of their outputs. SimaPro [26], along with the DATASMART 2021 LCI package [27], was employed to carry out this LCA study. This database offers data on the GWP impacts of individual materials' manufacturing and transportation. DATASMART package include the US LCI database and US-Ecoinvent database [28] to regional electricity data specific to the United States market, but no data customized for Canadian market.

As the data for CLT panels was not included in the current DATASMART Package, environmental impact information of the MTPs in this study was gathered from Environmental Product Declarations (EPD) of CLT and GLT made by Nordic structures [29, 30]. The Engineering Commons Building's curtainwalls' environmental impact data was collected using the EFCO corporation's EPD for curtainwalls [31].

Athena Impact Estimator [32] was used as the second software for conducting LCA analysis in this study. This software features an original database developed by the Athena Institute, which are localized for several major cities across the North America continent. This software can automatically calculate environmental impact of transporting materials from manufacturer to construction site based on the city selected by the users. This characteristic makes it easier to use than SimaPro but makes it impossible to modify the data input to fit the regions that are not included on the list in the software. Furthermore, the transportation (A4) life cycle stage was not included in the scope of this study.

2.3 Life Cycle Impact Assessment

By conducting the Life Cycle Impact Assessment, one can transform the result from LCI outputs into quantifiable impacts of different categories, such as global warming, human health, resource depletion, waste in water, etc. Both software programs used in this study assessed the environmental impacts from the building materials used in the whole building designs using the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), which was developed by the U.S. Environmental Protection Agency (EPA) [33]. Application of this tool will convert results from LCI to quantified environmental impacts. The impact indicators included in this study were GWP (measured in kg CO_2 eq), acidification potential (AP, measured in kg SO2eq), eutrophication potential (EP, measured in kg N eq), ozone depletion potential (ODP, measured in kg CFC-11eq), and smog potential (SP, Measured in O_3 eq).

2.4 Assumptions

Due to the limitation in collection of data, the following assumptions were made in this study:

Fasteners required for connecting steel frames to mass timber products were not included.

Since Fredericton is not included in the cities in the Athena Impact Estimator database, the building location for both structures were set as Halifax, Nova Scotia, Canada, the closest city to Fredericton.

2.5 The Building Inventory Data

The two different databases used in this study name building materials in different ways. To ensure the fairness for comparison, the material input in both databases was carefully selected after confirming the function and content of the materials. For instance, when it comes to interior steel stud walls, calculations of amount of materials used in walls were conducted using stud spacing, height, and length data.

3 Results and Discussion

The environmental impacts from module A1~A3 for the two buildings studied were analyzed using SimaPro and Athena IE and are summarized in **Table 4** and presented in **Fig. 4** to **Fig. 6**.

Table 4. Environmental impacts per 1m^2 of floor space from module A1~A3 of the Engineering Commons and IUC New Forestry Buildings

Impact category	SimaPro		Athena IE	
	IUC New Forestry	Engineering Commons	IUC New Forestry	Engineering Commons
Acidification Potential (kg SO_2 eq)	9.02E-01	1.51E+00	1.35E+00	1.74E+00
Eutrophication potential (kg N eq)	-7.58E-04	8.20E-02	7.22E-02	1.05E-01
Global Warming Potential (kg CO_2 eq)	2.80E+02	2.97E+02	2.54E+02	3.00E+02
Ozone Depletion Potential (kg CFC-11eq)	9.35E-06	1.13E-05	1.40E-06	1.74E-06
Smog Potential (kg O_3 eq)	1.32E+01	2.18E+01	1.62E+01	2.50E+01

3.1 Cradle-to-gate LCA results of two buildings

The Engineering Commons Building shows worse impact in all categories in the LCA result output from both software programs. However, this study was not a comparison study as previously mentioned since these two buildings have different size and usage pattern. Also, the worse environmental performance might not be caused by the application of MTPs according to **Fig. 5** and **Fig. 6**, which contains information on the percentage of contribution in environmental impact caused by different assemblies in two different LCA software programs, where C&B stands for columns and beams.

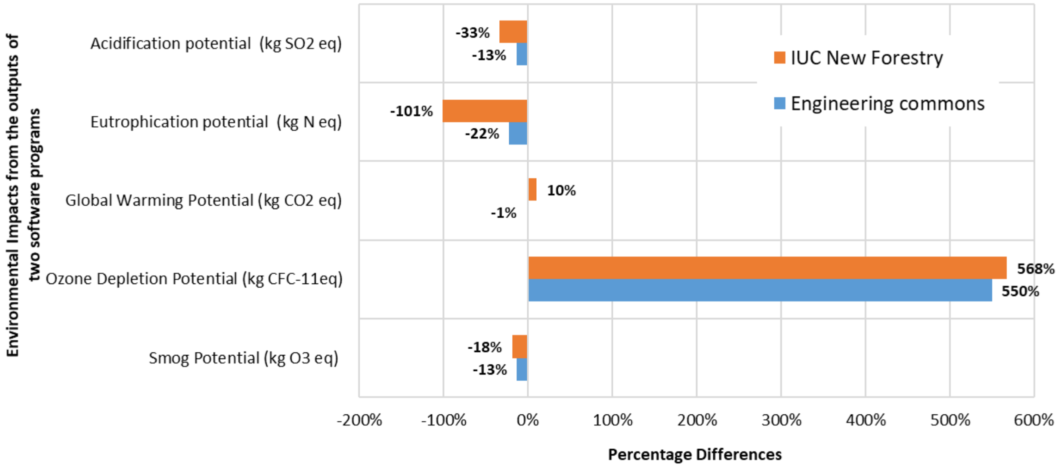

Fig. 4. Difference in environmental impacts from the outputs of the two software programs for both buildings (A1~A3).

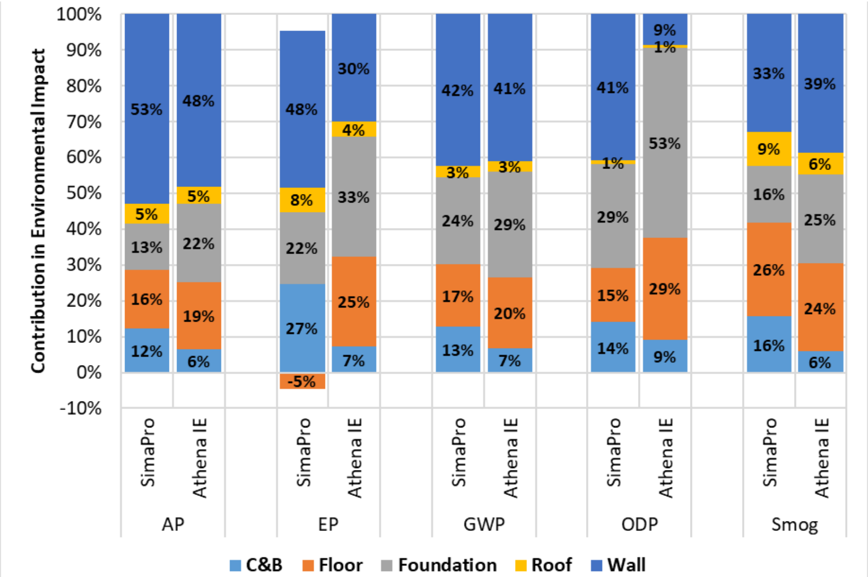

Fig. 5. Contribution to total environmental impact from different assembly group of the Engineering Commons Building (A1~A3) with data output from SimaPro and Athena IE.

As shown in **Fig. 5**, the major structural components in the Engineering Commons Building, which uses MTPs for floors, columns, and beams, would contribute around 20%~30% to the overall environmental impact in each category, while the same components made of traditional building materials in the IUC New Forestry Building contribute around 40%~50% in each environmental impact category besides EP as shown in **Fig. 6**. Another environmental advantage of MTPs is the carbon sink capability of these materials. EPD of the GLT beams and CLT panels [29, 30] shows that these two products would sequence 741.36kg of CO_2 per cubic meter of material. With this characteristic considered, the GWP of the Engineering Commons Building (A1~A3) will be lowered to 1.32E+02 kg CO_2 eq/m^2 during the service period (say, 50~60 years) of the building, which is 52.9% lower than the value (2.80E+02 kg CO2 eq/m^2) of IUC New Forestry Building. The destination of carbons stored in MTPs remains unknown as there is no information related to recycle or disposal of MTPs in the Province of New Brunswick, Canada, during this study.

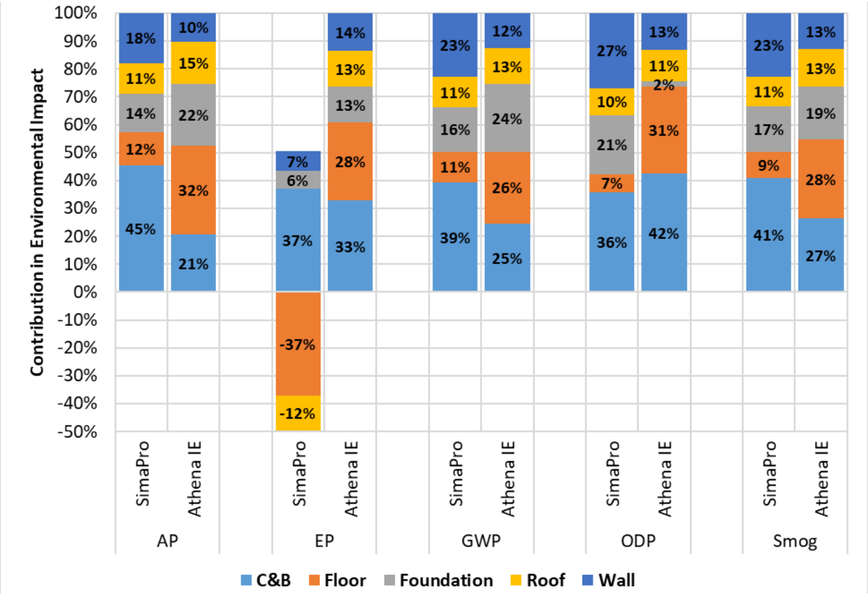

Fig. 6. Contribution to total environmental impact from different assembly group of the IUC New Forestry Building (A1~A3) with data output from SimaPro and Athena IE.

In the worst case scenario, however, if MTPs were all landfilled, the carbon they had stored could be gradually released back into the atmosphere due to the biodegradation of wood. Campbell [34] conducted a study of examining MTPs for the end-of-life scenarios, indicating that the demand for wood fibers and environmental legislation made it unlikely for MTPs to be disposed of in landfills. This indicates that recycling MTPs for wood fibers can help to maintain some of the carbon sinking benefit of MTPs even after the building's service life has ended.

3.2 Differences in output from two software programs used to model the Whole Building LCA

Since the same bill of material, the same boundary system defined, and the same impact characterization method were used in the input process for the two software programs used in this study, the only source of difference in the output results could come from the different LCI databases used in the process.

3.2.1 Difference in value of the data

As shown in **Table 4** and **Fig. 4**, when comparing the outputs generated from the software programs without considering transportation, a higher-than-10% difference in the output of both software programs can be observed in all the impact categories except GWP in both buildings. A large difference in EP of the IUC New Forestry Building can be observed due to the negative value output from SimaPro. This happens because the building material “galvanized steel sheet” has negative EP according to the result analyzed by TRACI method with data from DATASMART LCI database. A large difference in ODP from the two software programs can also be observed, which is due to their different LCI databases, requiring further research. The source of difference that could be identified could be due to the difference in LCI databases. This suggested that when comparing environmental performance of different buildings, it was necessary to ensure that the same software and database were used without any biases.

What can also be noticed from **Fig. 4** and **Fig. 5** is the difference in output from both software programs for the Engineering Commons Building is lower than the difference in outputs for the IUC New Forestry Building. This might be due to the application of EPDs of MTPs and curtain walls in the result generated from SimaPro. The developer (Athena Sustainable Materials Institute) of Athena EI software and publisher (FP Innovations Canada) of EPDs published a LCA report on CLT in Canada [35], suggesting that the data source for MTPs in two LCA software programs might be the same one.

3.2.2 Difference in contribution of each assembly

Athena Impact Estimator not only shows the stages A1-A3 when displaying the impact from each assembly, but also shows the life cycle impacts from each assembly, which include the material waste on construction site and replace/refurbish/remold during the use stage. It was not easy to separate those out from the Impact Estimator output. As shown in **Fig. 5**, the impact caused by MTP columns and beams are below 10% of the total impact in all categories for the Engineering Commons Building in Athena IE output. This contradicts the result from SimaPro where the columns and beams would contribute higher than 10% in all categories, especially 20% in EP. Contribution from foundation is also increased from 10% ~ 20% to 20% ~ 50% when switching from SimaPro to Athena IE. When it comes to LCA results for the IUC New Forestry Building, as shown in **Fig. 6**, the contribution from columns and beams decreased in all categories from ~40% to ~20% in all impact categories except ODP. Where ODP increased slightly to 42% Contribution from floors are also increased from 10%~20% to 20%~30%. These differences may impact the judgement of decision-makers. A suitable calibration should be made for a given LCA software program in the future.

Both software programs agreed that the wall section of the Engineering Commons Building would contribute to more than 40% of GWP and around 50% of AP. This could be attributed to that the glass curtain wall used in the Engineering Commons Building might be the cause of such a big contribution. However, application of glass curtain wall can reduce the energy required for indoor lighting and heating in winter, which will reduce environmental impact of operation of the building. A previous study [36] did show that extensive application of glass curtain wall could increase the heat load of a building in summer, but this negative effective could be mitigated with proper ventilation and the application of earth tube in the Engineering Commons Building. Without knowing the exact outcome, further study on whether the application of glass curtain wall can reduce environmental impacts of the building in the overall life cycle needs to be conducted.

In summary, the difference in output results generated from two software programs used in this study demonstrated that the same software, especially the same LCI database, shall be used for fair comparison on different buildings. Without a base value it is impossible to conclude which software has better accuracy in estimating the environmental impacts of two buildings than another. But when it comes to only estimating GWP of buildings in stages A1~A3, the two software programs used in this study may be used interchangeably.

4 Conclusions

Based on the above LCA analyses and discussion on two institutional buildings with two software programs, SimaPro and Athena IE, the following conclusions could be drawn:

1. Two software programs could draw similar conclusions on which building had relatively low environmental impacts per square meters of floor space.
2. Two software programs could be used interchangeably when only estimating GWP of a building in stages A1to A3.
3. Specific numerical output results had a noticeable difference (at least 13%) in all the impact categories except GWP even when both software programs used the same databases localized for North American market.

Acknowledgements

The authors would like to express their appreciations towards the Forest Products Laboratory, Department of Agriculture (United States), and the Faculty of Forestry & Environmental Management, University of New Brunswick, for their technical support.

Funding Statement

Funding was received from the Government of New Brunswick under its Environmental Trust Fund (Project number: #200100). Sponsors’ website: https://www2.gnb.ca/.

Funding was received from New Brunswick Innovation Foundation under its New Brunswick Innovation Research Chair Initiative Program. Sponsors’ website: https://nbif.ca/.

Credit authorship contribution statement

C. Gu: Conceptualization, Investigation, Formal Analysis, Writing – Draft. H. Gu: Supervision, Investigation, Technical Advice, Writing – Review. M. Gong: Funding Acquisition, Supervision, Writing – Review. J. Blackadar: Writing – Review. N. Zahabi: Writing – Review.

Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

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