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Current Trends in Forest Research

Laurent AB. Curr Trends Forest Res: CTFR-128.

Research Article

DOI: 10.29011/ 2638-0013. 100028

Comparative Life Cycle Carbon Footprint of a Non-Residential Steel and Wooden Building Structures

Achille-B. Laurent [1*], Yvonne van der Meer[1], Claude Villeneuve[2]

[1]Aachen-Maastricht Institute for Biobased Materials, Department of Biobased Materials, Faculty of Science and Engineering, Maastricht University, the Netherlands

[2]Chaire en éco-conseil, Département des sciences fondamentales, Université du Québec à Chicoutimi, QC, Canada

Corresponding author: Achille-B. Laurent, Department of Biobased Materials, Post-Doctoral Researcher on Bio-based Products Sustainability, Maastricht University, Brightlands Chemelot Campus, Geleen, the Netherlands. Tel: +31-433882240; Email: achille.laurent@maastrichtuniversity.nl

Citation: Laurent AB, van der Meer Y and Villeneuve C (2018) Comparative Life Cycle Carbon Footprint of a Non-Residential Steel and Wooden Building Structures. Curr Trends Forest Res: CTFR-128. DOI: 10.29011/ 2638-0013. 100028

Received Date: 20 November, 2018; **Accepted Date:** 30 November, 2018; **Published Date:** 11 December, 2018

Abstract

In the field of construction, wood products are known to have environmental benefits in comparison with materials like steel and concrete, especially to mitigate climate change. Since wood is an anisotropic material, comparisons with other building materials on a volume functional unit basis, such as a cubic meter of product, are not relevant. Wood structures also allow for architectural forms that are not feasible with other building materials. To enable a comparison between wood and steel, we have assessed the Life Cycle Carbon Footprint of complete non-residential building structures. This building frame was initially planned to be made from steel, but the architecture was modified to integrate glued laminated timber beams. The structural engineers provided material balance changes. The results show a significant reduction in greenhouse gas emissions for structures using wood as a building material.

Keywords: Carbon Footprint; Life-Cycle Assessment; Non-Residential Buildings; Wood Buildings Material

Introduction

In North America, wood components have always been ubiquitous in the structure of residential buildings. Today, this wood culture is maintained and renewed by the marketing of components or prefabricated wooden frame houses. The situation is different in the nonresidential building sector, such as institutional, commercial or industrial buildings. In the past decade, less than 4% of non-residential buildings in North America were made of wood [1]. In lasts years this has increased to 10% but for FP Innovations there is potential for at least a twofold increase in the use of wood for nonresidential buildings [2].

Several circumstances explain the low wood use in nonresidential construction in North America. Between the 1930s and the 1970s, modern architecture reinvented the design of public and commercial buildings, by utilizing the properties of concrete and steel structures [3]. This architectural revolution has gradually led to the erosion of wood structures in non-residential buildings [1]. Indeed, from the beginning of the 20th century only a few massive buildings were made from heavy timber (e.g. Butler building (1906) in Minneapolis, MN or 320 Summer Street (1906) Boston, MA). It resulted in a lack of knowledge about the potential of wood and engineered wood products, as well as many misperceptions associated with the technical characteristics of these structures. Thus, the expertise gradually vanished in the building sector.

The development of new elements of wooden structures, also called engineered wood, like glued laminated timber (glulam) or more recently Cross-Lam Timber (CLT), have revitalized the wood building market. These building systems make it possible for wood products to become economically competitive. Nowadays, the costs of wooden structures are similar or lower compared to steel or concrete structures [3]. Another advantage is the speed of erection. As the elements are pre-built in the factory, it remains only to assemble the different pieces of structure on site, hence accelerating the time of construction [3].

Among the presumed advantages of wood construction, it is recognized that, in comparison with competing materials, the low carbon emissions of the production line and the sequestration of CO_2 in the material during the whole life-span of the building may be integrated into a climate change mitigation strategy [4]. To compare the environmental impacts of competitive building materials, Life Cycle Assessment (LCA) is commonly used [5]. The functional unit used in LCA usually is a surface area of building [5] or volume or weight of materials [6]. An easy method to calculate carbon sequestration per cubic meter of wood products in a building is the use of the "displacement factor" [6]. This factor is an index to quantify the reduction of Greenhouse Gas (GHG) emissions obtained per unit of wood products substituted for non-wood products. A displacement factor of 2.1 tC/tC (metric tons of carbon emission reduction per tC of additional wood products used) was calculated by reviewing 66 studies around the world. However, other parameters such as type of building, external climate, or architectural aesthetic design can also affect the carbon footprint and this is not taken into account in the displacement factor. Additionally, assessing mechanical properties of building materials is complex and makes comparisons by physical unit (mass/volume) not appropriate, since nonequivalent functions are then assessed. Mechanical resistance is different if there is compressive (column) or bending (beam) strength for the materials [7] and this affects the sizing (section) of the structural components. Comparisons on a physical unit base are even more difficult, or not possible, for other architectural elements like arches, since not every building material can achieve such structure.

This study presents a detailed comparative assessment of GHG emissions and carbon sequestration in a life-cycle approach of a hybrid structure (made from wood and steel) and full steel frame for a non-residential building. The aim is to calculate the carbon emissions reduction that can be achieved with the use of wood material as a replacement for steel in a non-residential building. The comparative scenarios were prepared for the same building and were considered as building options for an arena located at the Université du Québec à Chicoutimi (UQAC) campus (Saguenay, Quebec, Canada). It was actually decided to choose to build the hybrid structure, which is presently fully functional and for few decades. This assessment has the particularity of using context-specific primary data. Indeed, the structural engineering company that sized the steel and hybrid structures provided the calculated mass balance for the design of the two structures. The calculation of wood impacts used a cradle-to-gate LCA of glulam company supplying arena beams [8]. These data were supplemented by field data collected during the construction of the arena.

The Life Cycle Carbon Footprint (LCCFA) study is performed in accordance to the ISO 14044 LCA guidelines [9]. Therefore, the first section is devoted to the definition of the objectives and scope of the study. It is followed by the inventory analysis describing the sources and methodology used in the data collection. In the third section, the impact assessment presents the results of GHG emissions calculated from data inventories of both building structures. Then the interpretation presents the analysis of uncertainty and sensitivity as well as additional elements of discussion, all to draw conclusions in the final section.

Definitions of The Objectives and Scope of the System

Objectives and scope definition are the first step of the presented LCA, according to the ISO 14040 series standards [9]. It allows a more elaborate approach than a carbon footprint based on the standard ISO 14067 [10], as the latter makes possible to calculate carbon footprint only related to the direct emissions, also referred to as scope [11]. The boundaries of this study include all direct emissions, indirect emissions from energy and other indirect emissions, also called scope 3.

Application Envisaged and Target Audience

This study aims to assess the carbon footprint of using wood components instead of steel components in a nonresidential construction. It provides decision makers quantified arguments of the steel substitution by wood to reduce greenhouse gas emissions and thus mitigate climate change. The study will take advantage of a life cycle approach that avoids shifting environmental impacts from one stage to another stage. However, this study does apply to a region-specific context. The glulam is modelled from primary data from the producer in Quebec, and the steel manufacturing is representative for the North America market context. The model of the construction stage is even specific for the building, since it was made from the data collected on the construction site.

The results of the comparative study are relevant for a wider audience interested in the use of wood in building structures to reduce climate change impacts.

Functions and Functional Unit

The main function of the studied system is to support the envelope of the UQAC arena during the lifetime of the building. The structure of the building has multifunctional characteristics. Only the primary function as support in the building was considered. The secondary functions of this structure, like aesthetics and acoustic quality, are not considered. Since aesthetics depend mostly on architects and is a subjective criterion and acoustic aspects are not a priority for a sports venue. The functional unit for this study is: "The structure of a non-residential building (an arena more precisely), covering an area of 3780 m^2 (or a volume of 23,000 m^3), for a life-span of 75 years".

Since this is an existing structure, the functional unit includes the area and volume of the building, which provides the opportunity to report the results to a physical allocation, in order to calculate the displacement factor.

Reference Flow

The reference flow represents the quantity of products necessary to fulfill the functional unit.

The lifetime of buildings in North America is not well documented. Only one study from the Athena Institute was performed on 227 demolished buildings, of which 94 were nonresidential. The results highlight the lack of correlation between the materials used in a structure and the average life-span of the building [12]. Demolitions reasons recorded were economic or social but less than one-third was demolished for physical failure. Those cases were mainly related to fire damage and touched more steel than wood structures. The Athena Institute study showed a longer lifetime expectation for wood nonresidential buildings, in comparison to steel or concrete. The majority of wood buildings reached 75 to 100 years but there are buildings that pass the 100 years regardless of the building materials. A conservative point of view was taken in the study in which it was assumed that the use of wood material in a nonresidential construction does not require additional replacement or maintenance compared to a steel construction. The reference flows for both types of structures were considered identical for an expected life span of 75 years. Both models include the quantity of materials needed to support the envelope.

Product Systems and System Boundaries

The boundaries are defined by the limits and the phases considered for the modeling of the system. The comparative carbon footprint covers the entire life cycles of the two building frames, thus a cradle-to-grave assessment. However, since it is a comparative assessment, we chose to exclude the use phase assumed to be equivalent, as further explained in the section general assumptions (Figure 1) shows the boundaries of the studied systems.

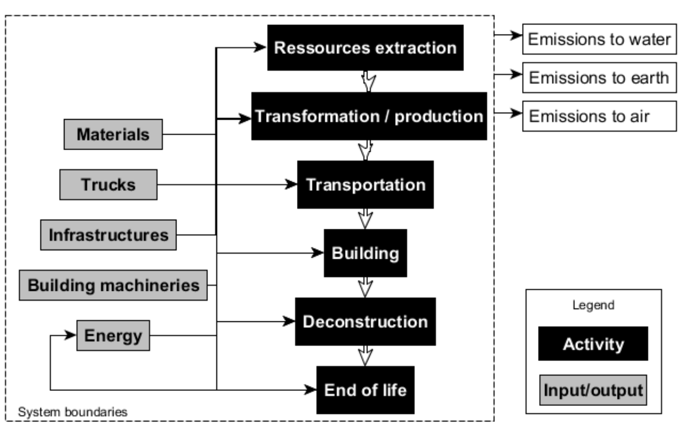

Figure 1: System boundaries of the study

Activities Description: The resource extraction mainly covers the mining of iron ore resources and the harvesting of wood resources. Resources are then transferred to the transformation/production activity, which brings together the various stages that take place at the processing and manufacturing sites of the two construction materials studied. Data for extraction and production of the various steel elements (hollow structural steel, flange sections, as well as screws and bolts) are retrieved from the USLCI database (National Renewable Energy Laboratory, Golden, Colorado) as these are representative for average North American steel. The inventory includes a steel recycling rate of 76% [13]. The data for wood beam production are taken from the cradle to gate LCA study of Quebec boreal forest glulam [8]. This inventory is provided from the factory that produced the glulam beams for the arena. It is important to note that both steel and wood structures are preassembled at the factory. This includes other materials (e.g. glues for the glulam beams), energy and infrastructures dedicated to these transformations or productions.

Once construction materials are ready to be assembled, they are transported to the construction site. Transportation of materials is done by truck, from Toronto (ON) for steel and Chibougamau (QC) for glulam. The model includes an allocation of trucks and road infrastructures to this activity.

Since the wood structures are pre-assembled, the building activity consists of assembling the beams together. The construction machines and the energy consumed are modeled. The data are primary data taken on site during the construction of the hybrid structure. The deconstruction activity inventory is modelled as identical to the building activity, as further explained in section general assumptions.

The end-of-life activity integrates the impacts of landfilling and building materials recycling, including transportation and infrastructures. The end-of-life scenario is based on the most recent statistical data representative of the construction sector in the Saguenay-Lac-Saint-Jean (QC) area. Since it is difficult to know what will happen in 75 years, during the estimated deconstruction of the building, a sensitivity study on this scenario is carried out in the results section to estimate the influence of this scenario on the total carbon footprint. Non-landfilled wood, 2% according to [14], is modeled as a source of energy production.

Geographical Limits

The geographical boundaries of the study need to include the origin of all resources. The study also needs to properly model activities that are different from region to region, such as transportation, energy generation (electricity grid) and waste management systems. Moreover, the sensitivity of the environment to different emissions varies from one geographic zone to another.

To take account of these geographical aspects, the databases used must be adapted as much as possible. This study focuses on the harvesting, processing, production, distribution, and end-of-life management in Quebec of a structure whose components originate mainly from North America. Until 2007 Quebec's crude oil supply came mainly from the North Sea and North Africa [15]. To stick as much as possible to the local context an adjustment was made based on the ecoinvent database (ecoinvent Centre, St-Gallen, Switzerland) inventories in Simapro software V7.3 (PRé Consultants, Amersfoort, The Netherlands).

Time Limits

The time period defined by the functional unit corresponds to the useful life expectancy of the building, that is 75 years. Since the reference flow is the same for the two types of structures studied, the temporal boundaries are defined for the estimated lifetime of the building. It is important to note that:

- Some processes can generate emissions over a long period. Landfilled organic material, such as wood, may emit different GHGs over a very long period, depending on the decomposition conditions. Some of these GHGs may or may not be transformed by flaring.
- The construction of the arena took place in 2009 so we chose this year as a reference. This static LCCF is representative for the year 2009. Any major change in one of the processes may change the results for other reference years.

The Life Cycle Impact Assessment (LCIA) should theoretically be considered over an infinite period of time to take into account the full extent of the effects and persistence of these events. In practice, we use models adapted to the substances analyzed, thus reducing the uncertainties. Since this analysis focuses on GHGs, the potential effects of emissions can be quantified for periods of 20, 100 or 500 years. In this study, we use the impact method "IPCC 2007 GWP 100a [16] based on [17]. This time period is mandated by the ISO standard (ISO 14044) and is the most suitable for the lifetime of the building of 75 years. It is also the time horizon for the global warming potential of GHG in main international conventions (UNFCCC, Kyoto Protocol, Western Climate Initiative), as well as in the most recognized carbon footprint quantification tools such as PAS 2050 [18] and the GHG Protocol for Product Accounting and Reporting [19]; other temporal considerations are not itemized [20].

General Assumptions

This section presents general assumptions regarding the carbon footprint assessment, as well as the characteristics and parameters of the materials of structures studied.

- The use phase was not included in this assessment because the structural materials are not determinative in the choice of materials used for the building envelope or for insulation. As this is a comparative assessment and both use phases are equivalent, both are removed from the study. In fact, this assumption can be considered conservative and favorable to the steel structure, since the steel framing in the wall reduces the insulating resistance (R-value), and this is usually compensated by design techniques [21].
- The amount of concrete required for the construction of foundations does not differ from a steel or a wooden structure [22]. The amount of concrete for the foundation is more dependent on the soil and the possibility of earthquakes [22]. Therefore, concrete was not included in this study as it is the same for the two studies in this comparison.
- The lifetime of the arena is similar, regardless of the structural material chosen. The fatigue resistance of the two materials in question is most likely exceeding the lifetime of the building, as discussed in the Forintek report [23]. Biogenic carbon sequestration is not considered, but is estimated in the discussion section. For all practical purposes in a dynamic analysis the estimated lifespan of a non-residential building in North America can be estimated at 75 years [24].
- A few studies mention that deconstruction is more labor intensive than demolition [25]. The deconstruction phase is not well documented in North America [26]. Therefore, we took the assumption of the deconstruction phase to be identical to the construction phase. The model reuses equipment and cycles times of the construction phase.
- The modeling of different machineries (skidders, cranes, etc.) used in all life cycle processes is not directly integrated into the ecoinvent database. We therefore resorted to a generic model "diesel burn in building machine" from ecoinvent.

Inventory Data of the Carbon Footprint

This section provides an overview of the sources of the data that were used, as well as an analysis of their quality.

Data Sources

Primary data were mainly collected from the producer of glulam beams used in the arena structure. The collection of these data was carried out during different visits to the producer with support of those responsible for the various stages of harvesting and processing as well as accounting data. The construction phase was the subject of particular attention, with precise monitoring of the assembly and fuel consumption. Missing, incomplete or not easily accessible data have been supplemented by the most representative assumptions and secondary data available in the cited literature or databases (ecoinvent and USLCI). We used ecoinvent and USLCI databases for different elements of the modeling of the two compared structures. All the production processes of consumed resources and waste management, as well as the transport involved in each phase of the life cycle of both structures were modeled with available secondary data.

Arena Structures Mass Balance

The components used to model the hybrid structure, the constructed arena, are detailed in (Table 1). The building's hybrid structure is composed of a hollow steel structure, a wide steel section and wood glulam beams assembled by screws, nuts and bolts that are presented in the mass balance. The components used to model the full steel frame arena structure are detailed in (Table 2).

Material	Quantity	Unit
Glulam section	110.95	m3
Hollow structural steel	5.68	Metric ton
Wide flange section	83.22	Metric ton
Screws, nuts & bolts	4.24	Metric ton

Table 1: Hybrid structure mass balance.

Material	Quantity	Quantity
Wide flange section	196.88	Metric ton
Screws, nuts & bolts	10.04	Metric ton

Table 2: Steel structure mass balance.

In comparison with the modeling of the current arena, the 111 m^3 of wood glulam used for the structure above the ice has been replaced by 114 tons of steel. The other structural components for the administrative offices, for the machinery rooms, for the players' rooms and for the internal platforms are the same.

Delivery Stage

Fuel consumption was estimated with information received from suppliers of the two materials studied, distances traveled and national average fuel consumption by type of truck used. This energy consumption served as an input into the model and was adapted to represent North American truck transport. The delivery distance of the steel was modelled from Toronto (ON) to Chicoutimi (QC) (1 003km) since a large majority of the steel used in the arena structure comes from the Great Lakes region (personal communication with Picard Steel, 2011). The transport distance of glulam is real because it is determined from a known production site in Chibougamau (QC) (358km from Chicoutimi). Both delivery distances were estimated by using googlemaps.

Requirements for Data Quality

Data quality requirements, according to the ISO standard, must at least ensure their validity in terms of age, geographical origin and technological performance. Our study concerns the reference year 2009. The geographical context is an arena in Quebec. The construction is specific to the Saguenay-Lac-Saint-Jean region, but some data are aggregated for North America as a whole.

In general, the available Life-Cycle Inventory (LCI) databases are not representative of specific reality, as the analysis presented here would require. Data from ecoinvent, which is the most comprehensive database at present, presents averages of technology impacts that have not necessarily been updated and that are mostly derived from the European context. We adapted this databank to the Quebec context for activities that took place in this province. The ecoinvent data concerning energy supply have been adapted to Quebec's energy grid (grid mix) to replace the various European energy sources. This includes, for example, modifying the distribution percentages of the various countries supplying crude oil resources [15] and sources of electricity production in Quebec, which was in 2009, 97% produced by hydropower [27]. Thus, all the foreground processes, such as industrial process and transportation, use background processes adapted to the Quebec energy context.

In addition, the type and consumption of the various vehicles used have been adapted from the ecoinvent database. For example, a noticeable difference is observable between the typical European city vehicles with gasoline modeled in the database and a pickup truck traveling on forest roads. Therefore, we made some changes, such as the mass of the vehicle and the fuel consumption to adapt it to the North American context. The vehicle modeling available in ecoinvent is based on a Volkswagen Golf; the weight is barely higher than one ton and the consumption is representative of the average consumption of European vehicles in 2005. We have therefore modified the quantity of steel in the inventory as well as all emissions by a factor of 2.14 so that it represents a pick-up whose consumption is on average 16.8 l / 100km (GHG protocol, 2009). In addition, we reduced the impacts to 10 percent attributable to the manufacture, use and maintenance of road infrastructures, since these pick-ups would only be running one tenth of the time on paved roads, according to silvicultural workers consulted. Data specific to several other vehicles, mainly related to forest transport, were also adapted for the purposes of the study. We have paid particular attention to disaggregate and document the data collected. (Tables 3) present the approach advocated and are inspired by Weidema [28].

Life cycle stages	Reliability	Completeness	Temporal correlation	Geographic correlation	Further technological correlation	Sample size
Steel production	3	3	3	2	3	2
Glulam production	1	2	1	1	1	1
Delivery	1	2	1	1	1	4
Building	1	2	1	1	1	4
Decontruction	3	4	5	1	5	5
End of life	3	3	5	3	5	5

Table 3: Data quality matrix.

Results

Since this study is limited to the impact of GHG emissions and their contributions to climate change, we used the " IPCC 2007 GWP 100a " method for modeling GHG emissions [16]. This method is the result of a consensus of the most recognized researchers in the field of climate change with a timeframe of 100 years. The "IPCC 2007" method mainly consists of characterizing the different GHG emissions contributing to global warming and then aggregating them into carbon dioxide equivalents (CO_2-eq) [16].

Application and Limits of the Carbon Footprint

Non-residential buildings are most often unique and complex, making comparisons difficult [29]. It is therefore not recommended to use the results of this study directly in a context different from this study. The interpretation of the results has certain limitations, as demonstrated by the sensitivity analysis in section sensitivity analysis. Transport is an element that can significantly vary, and may even reverse the carbon gains from the use of lumber in a building. In addition, the completeness and validity of the inventory data and the assumptions used also limit to the conclusions that can be drawn.

GHG Emissions Results

(Figure 2) presents the GHG emission results of the two types of structures studied. These results consider carbon emissions for all the processes described in the inventory for both types of structures over the entire life cycle. The hybrid structure, steel and wood, totaling 111 m^3 of wood glulam, reduced the amount of steel required for the construction of the arena by 55%, on mass based evaluation. This structure emits 120 tCO_2-eq, while that of steel would have emitted 203 tCO_2-eq. So using wood in the structure reduced the emission of 83 tCO_2-eq, or resulted in a 40% reduction of greenhouse gas emissions.

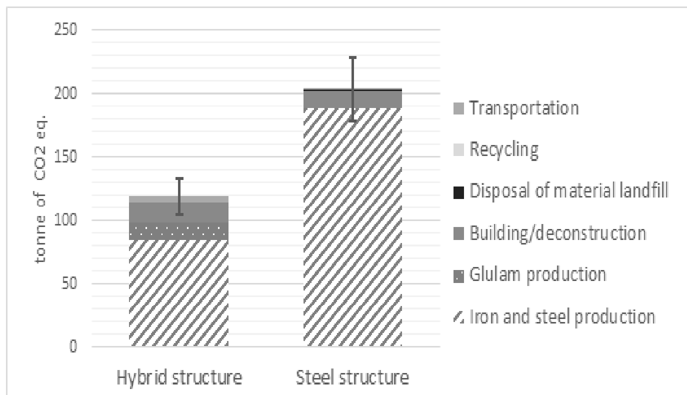

Figure 2: Comparative Greenhouse gas emissions of the hybrid and the steel structure.

The first finding is that steel production has the largest contribution to GHG emissions. It has a contribution of about 92% in the case of the entirely steel structure. In the case of the hybrid structure, steel production is also the main contributor with 70% of GHG emissions while it accounts for only 45% of the mass of materials. The contribution of glulam production is 13%. The second contributor, in order of importance, is associated with the stages of building and deconstruction in both cases.

In this study, transportation distances are short, so it is not a hotspot in the life cycle carbon footprint. Nevertheless, glulam beams are transported on longer distances and mainly by truck, as shown in [8], and therefore this phase may be a bigger contributor than glulam manufacturing emissions from cradle-to-gate. In these cases, it is advised to use an alternative mode of transportation that could help to minimize the reduction of emissions [30,31].

The end-of-life of wood products is probably the phase where it is easiest to reduce the carbon footprint, even if the impact is low. Indeed, the use of the wooden material for energy purposes would allow a possible substitution of fossil fuel, thus reducing the net carbon balance.

Uncertainty Analysis

Monte Carlo uncertainty analysis was performed in Simapro software to determine the extent to which a difference between two scenarios is significant, as explained by [32]. The results of this analysis are presented in (Figure 2), in which the "l" at the top of the bars represents the standard deviation on the GHG emissions result.

The USLCI data have the advantage of presenting processes that are more representative of North American practices. On the other hand, uncertainty is not available in this source, which removes much relevance to uncertainty analyzes on these data. With a variability of 2.54%, the uncertainty of the hybrid structure is higher than the steel structure, which is 0.72%. This difference is explained by the lack of variability given for the steel production in the USLCI database. Nevertheless, this lack of precision reinforces the relevance of addressing, through a sensitivity analysis, the variability of GHG emissions related to steel production. This analysis is integrated in the following section.

Sensitivity Analysis

As mentioned above several parameters used in the model present uncertainties. We have also put forward several assumptions to make it possible to determine the carbon footprint of the two types of structures studied. We tested the robustness of those parameters. The variability of the GHG emissions results demonstrates the importance of the modified parameters.

GHG Emissions from Steel Production

Initially we used the USLCI database because it is representative for North American practices. So for modeling the steel production we used the inventory name "Iron and steel, production mix/US". In order to verify the robustness of this main contributor a sensitivity analysis was performed on the steel production. We resorted to the reinforcing steel produced outside of Europe (ROW stands for Rest of the World) of the ecoinvent database. With the IPCC method, the GHG emission factor is two kgCO_2-eq. / kg of steel, compared with 0.91 kgCO_2-eq. / kg of steel based on the USLCI data. This notable difference is due to a recycling rate of 56% using the cut-off rule in the USLCI model, as explained in the documentation [33]. On the other hand, the recycling of steel is not taken into account in ecoinvent [34], probably because of a lack of reliable data. The reality is probably between these two values, which justifies the use of a sensitivity analysis.

(Figure 3) illustrates the results of the sensitivity analysis on emissions from steel production.

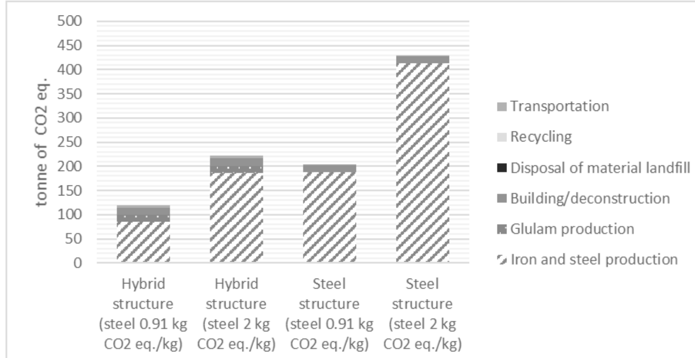

Figure 3: Steel production sensitivity analysis.

As shown in the results, GHGs emitted during steel production greatly influence the carbon footprint of both types of structures. When ecoinvent data are used to model the hybrid structure, its carbon footprint becomes greater than the original all-steel structure. However, when compared with the full steel structure calculated with the ecoinvent data for steel production, the hybrid structure maintains a significant advantage in terms of GHG emissions. That result shows how the model for steel production influences the GHG results.

End of Life Scenarios of Wood Glulam

End-of-life scenarios can vary from landfilling to energy valorization. As we cannot determine the material valuation rate that will be applied when the arena is demolished, we propose to evaluate the variation between 0 and 100%. We have assumed that the GHG emissions are a linear function of reduced landfill, which gives the slope represented in (Figure 4).

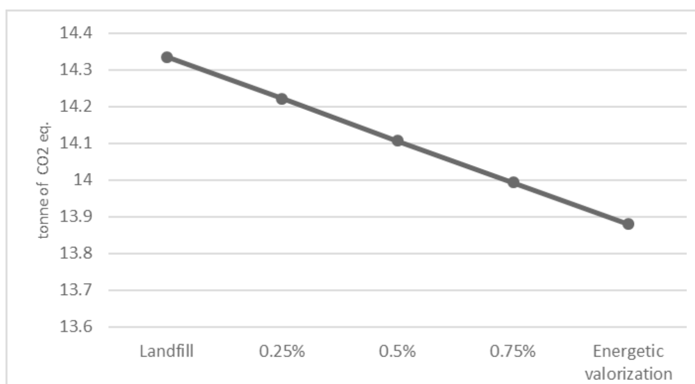

Figure 4: Sensitivity analysis of wood glulam end of life scenarios.

In contrast with the very conservative scenario "everything to landfill", the 100% valuation scenario can be qualified as very optimistic. Indeed, the modeling of an energetic valorization of all the glulam would be only thermal, since the reduction of the carbon impact for electricity is not advantageous in terms of substitution in

Quebec, because of the already very low GHG impact of electricity supply in the province. The use for energy purposes of 111 m^3 of wood allows the substitution of 800 GJ of fossil fuel, or about 30 m^3 of natural gas. In addition, we considered that the combustion of wood glulam is possible directly near the site of the UQAC (hospital complex boiler), without significant transportation and wood chips are produced with an electric grinder.

This valuation provides GHG emission reductions of 2.4 tCO_2-eq, a reduction of 1.7% in the balance sheet of the hybrid structure. This is a low contribution on the final result.

Discussion of The Results

In this section, we will expand the scope of the study. In the first part, we will try to answer the question: what could be the carbon footprint of a whole-wood structure? The second part of the section aims to calculate the potential sequestration of carbon in the structure by integrating biogenic carbon into the accounting.

Entirely Wooden Structure

Modern wood construction techniques make it possible to build large wooden structures. Some arenas, such as the Richmond Olympic Oval (BC) or the Anaheim ice arena (CA) have a structure with a large proportion of wood. There does not seem to be any disadvantage from the point of view of the technical feasibility of proposing a structure entirely made of wood, even if there is still a need for steel for screws and supports.

It is possible to determine the amount of wood glulam required for a whole-wood structure, by using the software Athena (Athena Sustainable Materials Institute, Ottawa, ON). Given the contribution of steel in the hybrid structure to GHG emissions, it is interesting to conduct the exercise as to determine the carbon footprint of such a structure.

Modeling The Structure of the Arena Completely in Wood

The components used to model the structure of the arena completely in 100% glulam are detailed in (Table 4).

Material	Quantity	Unit
Glulam section	186.65	m^3
Hollow structural steel	9.84	Metric ton
Screws, nuts & bolts	**4.24**	Metric ton

Table 4: Wood structure mass balance.

In comparison with the current arena hybrid structure, the 83 tons of steel used for the structure of administrative offices, machinery rooms, players' rooms and internal platforms were replaced by 76 m^3 of glued laminated wood in the modeling carried out with the Athena software.

Carbon Balance of the Entirely Wooden Structure

In order to add the entirely wooden structure to the carbon footprint comparison in this study, the same methodology, functional unit and assumptions were used.

(Figure 5) presents the result of the carbon footprint of the whole-wood structure in comparison with the two structures studied earlier. It is easily identifiable that the carbon impact of the structure made entirely of wood is lower than the two others, with emissions of the order of 58.6 tons of CO_2-eq. So, the wooden structure would have emitted only half of the GHG emissions from the real (hybrid) structure and one quarter of the total GHG emissions of the steel structure. The figure shows a distribution of the contribution of the impacts and results show that the production of glulam greater contribution to the wood structure GHG impact (37%) than steel production with 22% of the overall GHG impact. This is due to the low amount of steel needed for this structure.

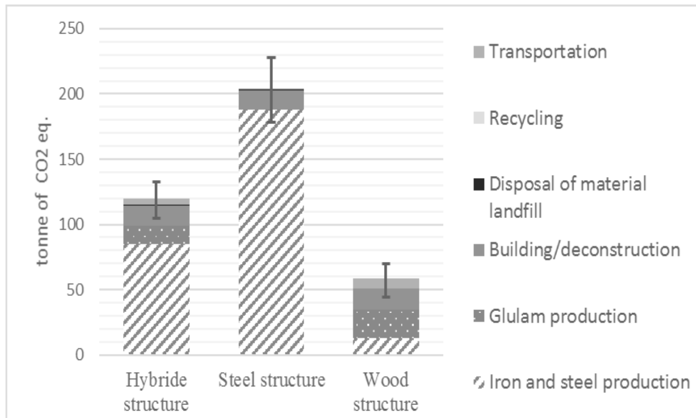

Figure 5: Wood structure carbon footprint comparison.

These results suggest that maximizing the use of glue-laminated wood in the construction of non-residential buildings with related structural configurations appears to have positive effects on the carbon footprint.

Biogenic Carbon Accounting

Accounting for the biogenic carbon sequestered in harvested wood products is still under discussion [35-37]. From each standard, biogenic carbon must be accounted, but must be separately presented [38,39]. Since the Quebec forest is sustainably managed and registered under recognized certification, mainly Forest Stewardship Council (FSC), Canadian Standards Association (CSA) or Sustainable Forestry Initiative (SFI), the wood procurement does not result in net deforestation in addition to other environmental criteria such as biodiversity, aquatic effects and soil impact [40].

Obviously, wood contains carbon, because each carbon atom in the wood is derived from an atmospheric CO_2 molecule captured by photosynthesis. It is generally accepted that wood is composed of 50% biogenic carbon by dry mass in average [41]. Based on of the Quebec's glulam LCA study, the density is 520 kg/m^3 and contains 22.5 kg of residual glue. That corresponds to 249 kg of carbon, or 914 kg CO_2 per m^3 of glulam. By subtracting the 102 kg emitted throughout the entire manufacturing cycle, a cubic meter of Quebec's wood glulam sequesters a net 812 kg of CO_2 [8].

According to these estimates, (Figure 6) presents the integration of biogenic carbon in the LCCF results. This calculation makes the wood structure even more advantageous by doubling the difference between the hybrid and steel structure total carbon emissions. By sequestering more carbon than anthropogenic emissions in the whole-wood structure, it could be carbon negative. In terms of mitigation of climate change this makes the use of wood even more interesting than other types of materials as carbon negative measures are requested to fulfill the goal of the Paris Accord to keep climate warming "well under 2 degrees before 2100". It should be noted that when the material is decomposed after use, e.g. by energy valorization, the sequestered carbon is released again. However, when all such structures would be wood-only, it could significantly contribute to carbon sequestration over time periods of 75 years.

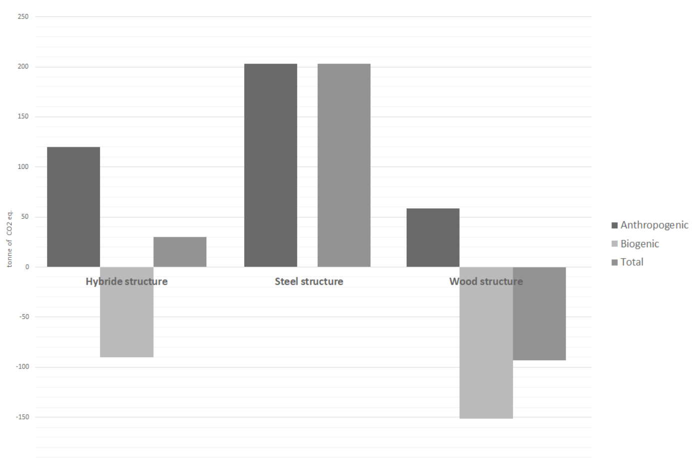

Figure 6: Biogenic carbon integration.

Conclusion

This study aimed to quantitatively determine the life cycle carbon footprint of the hybrid structure of the Université du Québec à Chicoutimi arena and to compare it to that of an entirely steel-made structure modelled for the same building. Based on the nature of the specific data used for a building constructed in 2009 but expected to remain functional for a few decades. As such, this comparative assessment will remain relevant for a long time, as building materials technology, such as glulam, is still under development in the non-residential construction sector in North America. The results of this case study show a net reduction in GHG emissions by using wood materials in the structure of a non-residential building. The construction of the hybrid structure has saved 83 tons of CO_2-eq, or 173 tCO_2-eq when the positive effect of biogenic carbon sequestration is taken into account.

Given the result of the comparison with the entirely wooden structure, the University could have reduced the impact of climate change by an additional 61 tCO_2-eq (and 122 tCO_2-eq, including biogenic carbon) by using more wood in its arena structure.

Although the wood material has already been documented as a lower emitter than steel over the entire life cycle, within the context of Quebec it is particularly favorable as non-residential building material. The availability of raw materials and their renewable nature are fundamental elements, and the low carbon intensity of electricity in the Quebec network contributes to consolidating these advantages. Indeed, much of the energy consumed by the forest industry is electrical, especially for sawing. The general conclusions were drawn from a site-specific study. However, this study can reinforce the interest for non-residential wood buildings in the light of greenhouse gas emission reduction, especially when wood procurement can be certified for sustainable management of forests.

Finally, regarding the displacement factor mentioned in the introduction, the indices calculated from the results of this case study are between 0.83 tC/tC for the hybrid structure and 1.76 tC/tC for the structure entirely made from wood, including biogenic carbon sequestration accounting. The displacement factors in this study are therefore below the average of 2.1 tC/tC calculated by Sarthe & O'Connor (2010) and this demonstrates the need for precise carbon footprint accounting to achieve GHG reductions with wooden building materials.

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