Cradle-to-Gate Life-Cycle Assessment of a Glued-Laminated Wood Product from Quebec's Boreal Forest

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Abstract

The building sector is increasingly identified as being energy and carbon intensive. Although the majority of emissions are linked to energy usage during the operation part of a building's life cycle, choice of construction materials could play a significant role in reducing greenhouse gas emissions and other environmental end-point damages. Increasing the use of wood products in buildings may contribute to the solution, but their environmental impacts are difficult to assess and quantify because they depend on a variety of uncertain parameters. The present cradle-to-gate life-cycle analysis (LCA) focuses exclusively on a glued-laminated wood product (glulam) produced from North American boreal forests located in the province of Quebec, Canada. This study uses primary data to quantify the environmental impacts of all necessary stages of products' life cycle, from harvesting the primary resources, to manufacturing the transformed product into glulam. The functional unit is 1 m^3 of glulam. This is the first study based on primary data pertaining to Quebec's boreal forest. Quebec's boreal glulam manufacturing was compared with two other LCAs on glulam in Europe and the United States. Our results show that Quebec's glulam has a significantly smaller environmental footprint than what is reported in the literature. From an LCA perspective, there is a significant advantage to producing glulam in Quebec, compared with the European and American contexts. The same holds true in regard to the four end-point damage categories.

To date, there is no available life-cycle analysis (LCA) on glued-laminated wood (glulam) production in the North American boreal forest zone. Information on the related environmental impacts of glulam production would permit informed decision making when choosing construction materials. This study is the first known cradle-to-gate LCA on the production of glulam based on primary data from an important manufacturer in the boreal zone of eastern Canada, in the province of Quebec.

Sustainable forest management can contribute to global warming mitigation efforts through the increase in forest carbon stocks and the consequent higher availability in harvested wood products (HWPs; Nabuurs et al. 2007). A number of studies have shown the benefits of using HWPs as a substitute for fossil fuels and building materials of higher carbon intensity, like concrete and steel, in long-term strategies (Niles and Schwarze 2001, Valsta et al. 2008, Sathre and O'Connor 2010). The HWP carbon pool, both as construction materials and fuel substitutions, has the potential to generate a cumulative and permanent reduction of greenhouse gas (GHG) emissions (Schlamadinger and Marland 1999, Kirschbaum 2006).

The building sector is known as an energy- and carbon-intensive sector, which has significant potential for reducing GHG emissions (Levine et al. 2007). The selection of low carbon footprint construction materials is an important initial step in reducing the environmental impact of a

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Forest Prod. J. 63(5/6):190–198.
doi:10.13073/FPJ-D-13-00048

building's entire life cycle. The carbon intensity of the most popular building materials, like concrete and steel, are well known and have been extensively analyzed and quantified (Worrell et al. 2001). The environmental impact of HWPs is difficult to quantify because it depends on a wide variety of local parameters like distance of harvesting, wood dimension, transformation technologies, distance to the storage and construction locations, and the different end-of-life scenarios. As a result, LCAs on HWPs are very scarce in Canada (Ter-Mikaelian et al. 2008) and results from existing LCAs may not be generalized.

Most North American residential buildings are wood-framed constructions (van de Lindt and Dao 2009). Conversely, only 5 percent of nonresidential buildings are made of wood frames in the province of Quebec, Canada (Direction du développement de l'industrie des produits forestiers 2008). In recent years, nongovernmental organizations and politicians have increased their promotion of wood building material for nonresidential frames, generating increased interest for glulam products.

The present study focuses exclusively on a wood product, glulam, sourced from Quebec's boreal forest, in the closed crown black spruce–feathermoss domain. This ecosystem is characterized by predominance of a coniferous tree species, black spruce (*Picea mariana* (Mill.) B.S.P) (Rowe 1972). This particular species is very resistant to cold and has a short growing season, thus producing a relatively small diameter log over a long period (Viereck and Johnston 1990). Once black spruce is transformed into glulam, the product possesses valuable mechanical properties (Zhang and Koubaa 2008). Additionally, it has been shown that the harvesting stage of a black spruce stand, from an LCA perspective, emits the GHG equivalent of an extremely small fraction of the carbon content of a trunk (Gaboury et al. 2009). Another particularity of the province of Quebec is that 97 percent of its electricity is generated from hydroelectric dams. Hydroelectric production emits a negligible amount of GHGs compared with conventional fossil fuel–based electricity generators (Environment Canada 2009).

There is a double advantage of a cradle-to-gate LCA. First, it allows direct comparison between different sources of glulam in building construction LCAs or carbon footprint analysis. The second advantage is for glulam producers, who can identify environmental hotspots within the glulam manufacturing process (from resource extraction to finished machining). As inventory covers 5 years of operations, producers can follow the evolution of the environmental impacts of their manufacturing processes. Additionally, they can compare their results to competitors everywhere in the world.

The objective of this cradle-to-gate LCA is to quantify the environmental impact of all necessary stages, from harvesting the primary resources to manufacturing the transformed product into glulam. Chantiers Chibougamau Ltée (CCL), a softwood logging and engineered wood products manufacturing company located in Chibougamau, Quebec, Canada, was selected because it was the only producer using boreal tree species for glulam in the province at the beginning of the study.

Methods

The life-cycle inventory (LCI) is based on data collected in 2010 through surveys with CCL, which uses trees from Forest Stewardship Council (FSC)–certified woodlands located between the 48th and 52nd northern parallels in Quebec's central boreal forest. The primary data collected for this analysis were issued from the company's operations between the 2004 and 2009 fiscal years. The main advantage of collecting inventory over a period of several years is to mitigate the interannual variability bound to natural, economic, and technological fluctuations.

When the primary data were not available, the LCI was completed with data from the ecoinvent database (ecoinvent Centre, St-Gallen, Switzerland) and was adapted to Quebec's particular energetic grid, where production of electricity and supply of fossil fuel, as well as the weight and the consumption of pickups, trucks, and other vehicles that may substantially differ from a European context, were accounted for. LCI data were modeled into the LCA software SimaPro v7 (PRé Consultants, Amersfoort, The Netherlands). End-point impacts and damages were calculated with the Impact 2002+ method (Swiss Federal Institute of Technology, Lausanne, Switzerland) and subsequently interpreted according to International Organization for Standardization (ISO) 14040 and 14044 guidelines (ISO 2006a, 2006b). Moreover, sensitivity analyzes were performed as an economic allocation, and the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) 2 method was applied to test the relevance of the findings. Because current practices were applied to this case study, the error propagation was calculated by Monte Carlo analysis using 1000 simulation iterations (Jolliet et al. 2005). The uncertainty of inventory parameters were taken from the Intergovernmental Panel on Climate Change (IPCC) guidelines, including means, standard deviations, and distribution for the parameters. The probability of each impact was derived from the Monte Carlo simulations, which gave the upper bound of possible errors.

Functional unit

The chosen functional unit is 1 m^3 of glulam, which includes lumber and glue, in accordance with the FPInnovation's (2011) Product Category Rule. All input and output data for the production of a glulam beam are based on the volume of products and coproducts (lumber, bark, shaving, and trimming) from the sawmill and the lamination unit in accordance with ISO guidelines (ISO 2006a, 2006b). This functional unit was selected to allow direct comparison with other LCAs on glulam and because the function and the reference scenario for the whole life cycle of this wood building product cannot be stated (FPInnovations 2011, Puettmann et al. 2012).

System boundaries

This cradle-to-gate LCA covers wood harvesting and transportation to the sawmill as well as production of lumber and coproducts at the glulam manufacturing plant. The cumulative system boundary encompasses all stages of glulam manufacturing, including infrastructures, materials, and energy needed (Fig. 1). The coproducts are defined as generated materials, distinct from the principal product, that leave the system boundaries (usually because they have some economic value or function).

Product process

The glulam production process is divided into two steps for the assessment. The first step takes into account harvesting

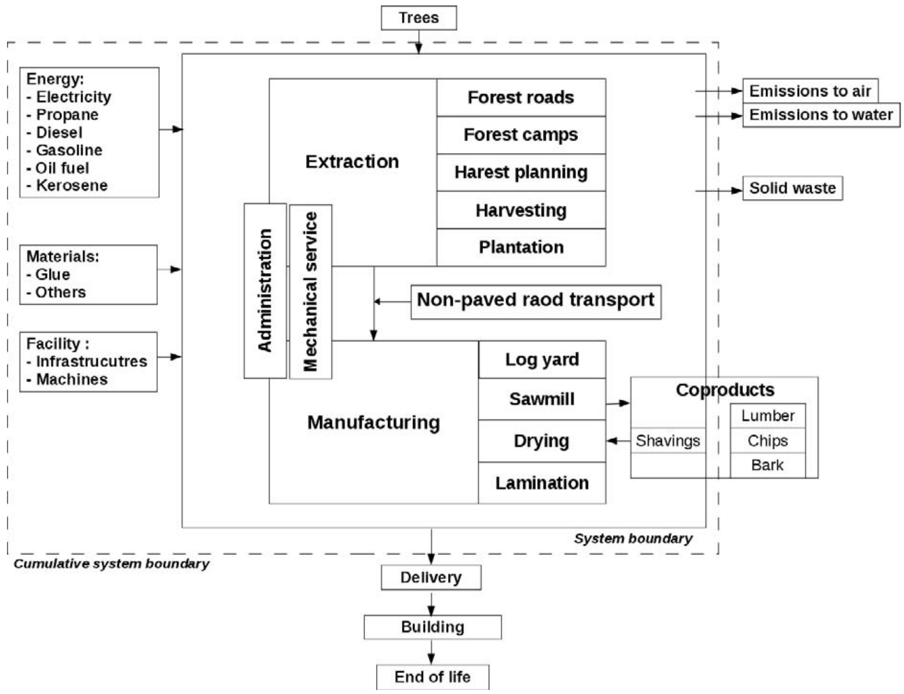

Figure 1.—Glulam boundaries.

and transportation of logs to the mill, while the second step pertains to the transformation to the final product. The first step is called extraction and the second, manufacturing. The administration and mechanical services data (energy and material consumptions) are taken into account in the inventory and are common to all steps of the glulam life cycle.

Extraction.—The extraction combines six stages (forest roads, forest camps, harvest planning, harvesting, plantation, and nonpaved road transport) that could be broken down into some other substages. However, the processes described in the forthcoming paragraphs only summarize the available aggregated information.

The forest road stage takes into account annual forest road construction and maintenance. These two processes include the energy consumed by construction machines while in operation as well as during the manufacturing of this equipment. While different kinds of machinery may be used in this stage, for simplification purposes, the model assumes all machinery is hydraulic building machines.

Only the different forms of energy consumed during use of the forest camps are taken into account for the modeling. The camps are mobile accommodations that are moved as close as possible to harvesting areas. For this reason, the environmental impacts of camp infrastructure were considered negligible.

Harvest operations are planned by a team of foresters. Planning is based on inventory data and performed at an office, but it requires some occasional travel to the harvesting areas. The modeling included traveling by full-sized pickup trucks for this process.

Modeling takes all inputs into account, from the tree harvesting (whole-tree harvest, hauling, delimbing and loading) to nonpaved log transportation. CCL whole-tree harvest operations include the trunks and stems. The glulam manufacturing process requires cutting the stems into relatively small blocks of wood, so CCL transports most of the harvested tree stems to the mill. As for forest roads, the modeling uses data for hydraulic building machines.

The plantation phase assumes that the forest area is sustainably managed (Food and Agriculture Organization of the United Nations [FAO] 2007), hence without human-induced long-term loss of forest carbon stocks. The primary consumption data during this phase are from an LCA on forest management in the same forest area (Gaboury et al. 2009) based on the activity of CCL. An average of 30 percent of the harvested land area is reforested, the remaining area regenerates naturally (F. Laliberté, personal communication, April 20, 2011).

CCL has direct access to the forest via nonpaved roads. The harvesting ground distance is, on average, 150 km to the mill. Hence, 150 km of log transport by off-road trucks (i.e., payload capacity exceeding 100 t) was modeled based on truck transportation data available in the ecoinvent database. Some adaptations were made to the load burden and the consumption to remove the impact of paved road use, but that of nonpaved road usage is accounted for as maintenance in the forest road phase.

Manufacturing.—Glulam involves three transformation processes. First, there is the lumber production at the sawmill. Typical steps consist of debarking, sawing, drying, and planing. The available data on energy consumption did not permit differentiating between the different steps, although drying was separated from the others because the energy it uses is important and must be isolated to be compared with other assessments. Separation was possible because the steam for drying is generated in a separate boiler. The second transformation includes jointing, a mechanical resistance test, and gluing, which yields a raw glulam beam. The third transformation is the machining of the glulam beam to produce a finished product, directly usable at a construction site. The second and third transformations are combined in this study in a stage called lamination.

After weighing, the off-road truck is unloaded in the log yard. During the log yard stage, logs are manipulated and selected according to market demand. This stage includes the diesel combustion for hydraulic building machines available in the ecoinvent database.

Debarking and sawing are the most significant processes during the sawmill stage. Most of the sawmill processes used are automated and the majority of the machines had to be modified by CCL, including a saw adapted for small softwood logs. These technological modifications increased the sawmill productivity. The energy consumed is almost all in the form of hydroelectricity. Although it occurs after drying, the wood shaving process is taken into account in the sawmill stage because the shaving machines are in the same plant as the band saw.

The manufacturer in this study generated most of the thermal energy required for the drying stage. The wood shaving dust is used for that purpose, a practice that has been in place for decades. The assumption of almost carbon neutrality when using wood fuel has a significant impact in the overall LCA because the drying process is the most energy intensive of all the processes in the wood manufacturing sector (Bergman and Bowe 2008). Nevertheless, some grade 1 oil fuel is consumed for the loader that manipulates the lumber.

Upon exiting the sawmill, part of the produced lumber is selected for glulam at the lamination unit. This selection is based on a nondestructive mechanical field stress test to determine the machine stress-rated lumber grade. Only the highest quality grade is sent to the lamination plant. The first process is end-jointing to produce the required length. Jointed lumber is then one-way vertically stacked and glued. Once dry, these vertical stacks are glued and one-way horizontally stacked according to the required dimensions. All gluing steps use isocyanate adhesive and are dried by microwave. Machining is the last step to adjust the glulam timber to exact architectural plan specifications.

Data collection

Data collection followed guidelines defined in ISO standards on LCIs (ISO 2006a). Primary data were collected for the period 2004 to 2009 by surveys, on-site visits, and meetings with 13 department managers at the glulam manufacturer throughout 2010. Harvesting and manufacturing managers provided data on energy consumption, raw material consumption, land occupation, and product and coproducts output. Inputs and outputs linked to energy usage such as electricity for rotating machines, infrastructure plant, heating fuel, vehicles, fuel, and glue production were obtained from the available ecoinvent database but adapted to the local context (Hedemann and König 2007). For example, electricity was modified to represent the grid mix of Quebec province, which is 97 percent hydropower. The origin of fossil fuels was also modified from ecoinvent to represent the supply in the province of Quebec.

CCL's glulam is mainly (>85%) composed of black spruce. To simplify the weighted-average calculations, wood density was assumed to be 406 kg/m^3, which is the anhydrous black spruce density (Nielson et al. 1985). Glulam density was provided by the producer at 520 kg/m^3. The difference between raw wood and glulam can be explained by the 22.5 kg of residual glue the latter contains and the compression of the fibers during the press process. All conversion units for forest products, logs, barks, chips, and shavings followed published factors specific to the forest products industry in Canada (Nielson et al. 1985).

Inventory

Fifteen liters of diesel per functional unit was used to operate the mobile machines in the forest and at the plant. Twenty kilograms of ovendry biomass fuel was used for heat input in the green lumber drying kiln. An energy backup was provided by grade 1 oil fuel, with a consumption of under 0.5 liter/m^3 of glulam on average. For the manufacturing of a cubic meter of glulam, 114 kWh of electricity is used by static machines such as saws, conveying equipment, presses, and microwaves; 1.5 liters of gasoline is consumed by pickup trucks or other vehicles; 0.4 liter of liquefied petroleum gas is used for cooking in forest camps and in forklifts and to head up equipment during winter operations; and 0.07 liter of jet fuel per functional unit is included in the inventory to account for travel of personnel and directors by plane.

In this study, isocyanates represented more than 99 percent of adhesive used in glulam production. The manufacturer of the adhesives is located in the Greater Toronto Area, Canada (located ca. 1,150 km away from Chibougamau). Transport was performed by trucks, which have a relatively small impact when compared with adhesive production itself, which is energy intensive. As CCL's glulam is produced from small-diameter lumbers (1 by 1 ft), it allows for a better homogenization of mechanical resistance but consumes more glue than glulam beams from other sources.

Coproducts

In the Canadian wood products sector, a large portion of coproducts is sold while the other portion is used on site (Meil et al. 2009). In this case, all coproducts of glulam have a function and a commercial value. Accordingly, coproducts are not considered as residues in this study. Following ISO guidelines, the inputs and outputs of the system were partitioned between the different coproducts in order to highlight the physical relationships between them. Coproduct repartition was calculated on a mass basis, as was the case with the other databases consulted (Consortium for Research on Renewable Industrial Materials [CORRIM] and ecoinvent), allowing for comparisons. Glulam production is not the main objective of CCL. The most important coproduct was lumber, the most profitable for the manufacturer. Wood chips represent the largest volume (Table 1) and were sold to a regional pulp mill. Bark was sold to an electricity producer 50 km from the mill. Shavings were used onsite as wood fuel for drying.

Results

The environmental damages are presented without normalization as suggested in the Impact 2002+ method user guide (see Humbert et al. 2005, for more details). The guide also gives further information on the calculation of damages. Results are presented in graphical form. A resource depletion category is not been presented because the results added no significant information, and the

Table 1.—Coproducts physical (mass) repartition.

Coproducts	Ovendry mass (metric tonnes/y)	Repartition (%)
Lumber	103,365	25
Chips	188,161	46
Shavings	53,859	13
Bark	52,030	13
Glulam	7,945	2
Total	405,359	

uncertainty bars were present only on the sums because calculations were only possible on the final damages.

Human health

The human health damage categories are a sum of midpoint categories, which could affect human health and are expressed in disability-adjusted life years (DALYs). The human health impact is known in the medical domain and used by World Health Organization (Humbert et al. 2005). The human health damage is 0.00022 ± 3.79E–5 DALY for a cubic meter of glulam (Fig. 2). The most important impacts result from the combustion of fossil fuel (over 40%), followed by the combustion of the biomass fuel (30%) and the adhesives (25%).

Ecosystem quality impact

The ecosystem quality category is the sum of aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acid/nutriment, and land occupation, which are midpoint categories affecting ecosystem quality. End-point damage is expressed in potentially damaged fraction of species on a square meter of land over the course of 1 year (PDF/m^2/y). The production of one functional unit affected ecosystem quality on 64.1 ± 17.3 PDF/m^2/y (Fig. 3).

Global warming

The production of 1 m^3 of glulam in this cradle-to-gate assessment emits a total of 102 kg ± 9.97 of CO_2 equivalent[1] (Fig. 4). The most important contributor is the consumption of diesel fuel with 55 percent of the total GHG emissions and the adhesive manufacturing with 38 percent of GHG emissions. Quebec hydroelectricity being almost carbon neutral (according to the hydropower model in ecoinvent), its usage does not affect the GHG balance significantly.

Resources

The resources category is the sum of nonrenewable energy and mineral extraction, both of which are affected midpoint categories. The resources are expressed in megajoules of primary nonrenewable energy. The production of 1 m^3 of glulam consumed 1,980 ± 302 MJ of nonrenewable resources, equivalent to 595 kWh.

[1] CO_2 equivalent emission is the amount of CO_2 emission that would cause the same time-integrated radiative forcing, over a given time horizon, as an emitted amount of a long-lived GHG or a mixture of GHGs. The equivalent CO_2 emission is obtained by multiplying the emission of a GHG by its global warming potential for the given time horizon. For a mix of GHGs it is obtained by summing the equivalent CO_2 emissions of each gas (IPCC 2007).

Discussion

Comparison with other glulam LCAs

Two other LCAs on glulam are available in life-cycle databases (ecoinvent and USLCI [National Renewable Energy Laboratory, Golden, CO]) and were used to put the present results in perspective. Quebec's boreal glulam has a smaller carbon footprint with respect to each of the damage impacts quantified (Table 2).

The results show that Quebec's glulam manufacturing emits 57 percent of the GHG emissions of European glulam in the ecoinvent database. A couple of factors can explain this important difference. The greatest positive impact on global warming is the use of shavings as fuel for the drying process. This practice avoids the emissions of more than 80 kg of CO_2 eq per functional unit, compared with the use of natural gas.

Most of the energy consumed by Quebec's glulam is renewable because it is in the form of hydroelectricity. This accounts for a significant difference when compared with electricity produced from fossil sources. A sensitivity analysis about electricity source shows that for an average European grid, the GHG emissions amounts to 162 kg CO_2 eq, close to the footprint of generic glulam product in ecoinvent. The composition of the electricity grid in different locations can thus be a determinant component of the carbon footprint of glulam product. The possibility for comparison with the two studies remains limited, considering the difficulty of accessing LCI data not published within both LCAs (Puettmann and Wilson 2005). Sensitivity analyses were performed to assess the reliability of the results (Fig. 5). By replacing Quebec's electricity by an average European grid mix, the carbon footprint is raised by 60 kg of CO_2 eq.

Given their optimized process, CCL utilizes a greater fraction of each stem for glulam production compared with many other industries in the same area and elsewhere. That additional part of the stems represents 12 percent of the log total mass used for glulam production. That part is normally left onsite in the harvesting process. The transportation of this extra log length from forest to mill results in a negligible increase of fuel consumption but minimizes the amount of harvesting operation needed per functional units of glulam produced (P. Morrissette, personal communication, February 2, 2011). This optimization results in a GHG emissions reduction of around 5 percent.

Sensitivity analyses

Isocyanate adhesive manufacturing consumes a high amount of energy, making that process a significant GHG source. However, if the isocyanate adhesive was replaced by European formaldehyde glue, the carbon emission from the analyzed functional unit would increase by 52 kg CO_2 eq. Thus, the choice of glue is an important factor impacting the LCA results of glulam production. By adding the European formaldehyde glue instead of the isocyanate adhesive, GHG emissions would reach 214 kg CO_2 eq, 15 kg CO_2 eq more than the reference case for European glulam. This difference can be explained by the smaller dimension of boreal forest logs, which results in more forest operations for a comparable wood volume, and by the greater harvesting ground distances to the mill (ca. 150 km on average for the CCL operations), a longer distance than in European

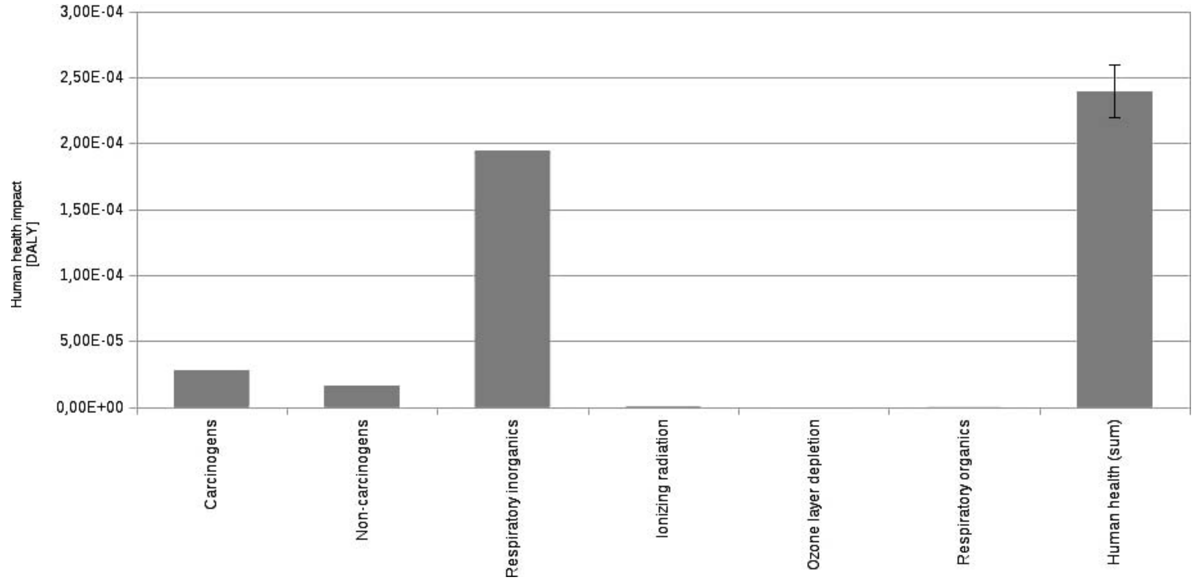

Figure 2.—Human health impact categories represented as damage (disability-adjusted life years [DALY]).

countries. Both differences require more diesel consumption per functional unit.

Economic allocation

Glulam is a wood product with high added value. While glulam production represents 2 percent of the volume of CCL activities, it corresponds to 15 percent of their product sales. That difference is due to the high value of sales per cubic meter of glulam, ca. CAD 900/m^3 compared with CAD 110/m^3 for the studs. Thus, the environmental damages of 1 m^3 of glulam were recalculated by an economic allocation to assess the changes on the observed results through mass allocation. The economic repartition of the different coproducts of CCL is presented in Table 3.

The environmental damages caused by CCL's glulam are greater via the economic allocation but are consistent with the results obtained by volume allocation (Table 4). Impact of the forest operations and drying at the sawmill increased proportionally with the economic allocation. The lamination still represented the biggest environmental impact of glulam production. Damages linked to this operation were not changed by the different allocation because 100 percent of the process is attached to glulam. However, the use of an economic allocation limits possible comparisons because other studies did not use this approach.

TRACI 2 method

The TRACI method has been developed to determine the potential impact on the environment (Bare 2011). The principle is the same as for Impact 2002+. However, the categories of damages differ because TRACI was derived from ecotoxicological studies of the US Environmental Protection Agency. Thus, categories of impact of this method are relevant to North America. We did not initially select this method, however, because Impact 2002+ is the most commonly used in the literature, especially for harvested wood products.

Table 5 shows the comparative results obtained with the TRACI 2 method. As can be seen, the order of magnitude remains substantially the same.

Other factors to be considered

Other aspects should to be taken into account for a complete LCA, namely delivery from mill to consumers, energy consumption of the building, carbon sequestration in

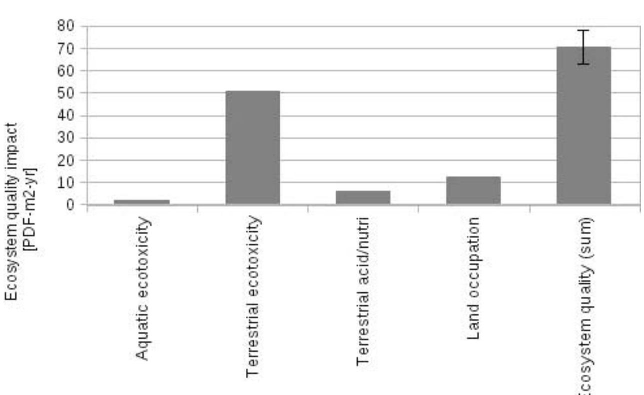

Figure 3.—Ecosystem quality impact categories represented as damage (potentially damaged fraction per square meter per year).

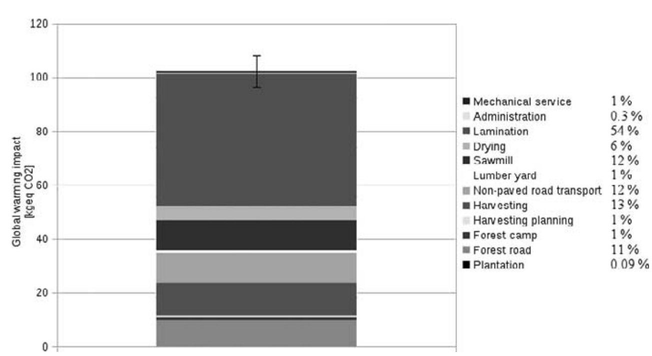

Figure 4.—Global warming impact category represented as midpoint/damage (in kilograms of CO_2 equivalents).

Table 2.—Comparison of results from life-cycle analyses (LCAs) of glulam from Quebec, Europe, and the United States.[a]

LCA	Quebec boreal	ecoinvent	USLCI (CORRIM)
Functional unit	m^3 of glulam	m^3 of glulam	kg of glulam (×517)[b]
Human health (DALY)	2.2E−4	2.95E−4	2.95E−4
Ecosystem quality (PDF/m^2/y)	64.1	491	185
Resources (MJ primary)	1,980	3,980	5,240
Global warming (kg CO_2 eq)	102	199	160

[a] CORRIM = Consortium for Research and Renewable Industrial Materials; DALY = disability-adjusted life years; PDF = potentially damaged fraction.

[b] 517 kg/m^3 is the average density of the Pacific Northwest and Southeast glulam in the CORRIM gate-to-gate life-cycle inventory (LCI) of glued-laminated timbers production (Puettmann and Wilson 2005).

HWP, and wood disposal at the end-of-life (Gustavsson et al. 2010). Energy balance, delivery, and carbon sequestration were added as supplements to this cradle-to-gate assessment.

Energy balance.—Energy balance is based only on scope 1 energy consumption. Extraction, refinery and transportation, machine building, and infrastructures are therefore not included.

The energy consumed for glulam production is in different forms, such as electricity, diesel fuel, propane, grade 1 oil fuel, gasoline, a small quantity of jet fuel, and wood fuel from shavings. Overall, fossil fuel represents 54 percent of the energy consumed (Table 6).

Distribution per stages reveals that the lamination is responsible for half the energy consumed. Most of the electricity is consumed during the microwave drying process (Table 7), as was also found in various LCAs (Taylor and Van Langenberg 2003, Bergman and Bowe 2008) with more than 21 percent of the total. Because the energy used comes from renewable sources, the GHG impact is less than 5 percent of glulam's carbon footprint. In contrast, extraction in the forest and its related processes essentially use fossil fuel sources, representing 50 percent of the total energy consumed, and therefore affect more than 80 percent of GHG emissions.

Table 3.—Economic repartition of coproducts.

Coproducts	Economical repartition (%)
Lumber	20
Chips	25
Shavings	1
Bark	0.01
Glulam	15
Other	38.99
Total	100

Delivery.—Delivery distance and conveyance were integrated into the survey. Although these data were not included in the LCI, the global warming impact was calculated. On average, Quebec's glulam travels 1,000 km by truck from the mill to the consumer, for approximately 150 kg CO_2 eq per m^3 (the trucks were considered half full on the way back). These emissions represent 140 percent of GHG emissions during glulam manufacturing. Hence, delivery distances have a large impact in a cradle-to-grave assessment. Not surprisingly, transporting HWPs by truck over long distances can be significantly detrimental from a carbon footprint perspective. The same holds true for other building materials and ought to be considered when trying to determine the break-even point of the global warming advantage of HWPs.

Biogenic carbon.—Obviously, wood contains carbon, and each carbon atom within HWPs originally came from a molecule of atmospheric CO_2. Wood is composed of 50 percent biogenic carbon by dry mass (Ter-Mikaelian et al. 2008). Because Quebec's glulam anhydrous density is 520 kg/m^3 and contains 22.5 kg of residual glue, a cubic meter of Quebec's boreal glulam corresponds to 249 kg of sequestered 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 as long as it is kept in use. Depending upon end-of-life scenarios, it may or may not be returned to the atmosphere.

Finally, land occupation and land use changes are not taken into account in this study because the chosen characterization method, Impact 2002+, does not consider this type of impact. In order to estimate the carbon footprint of resource extraction, there exist some models like the

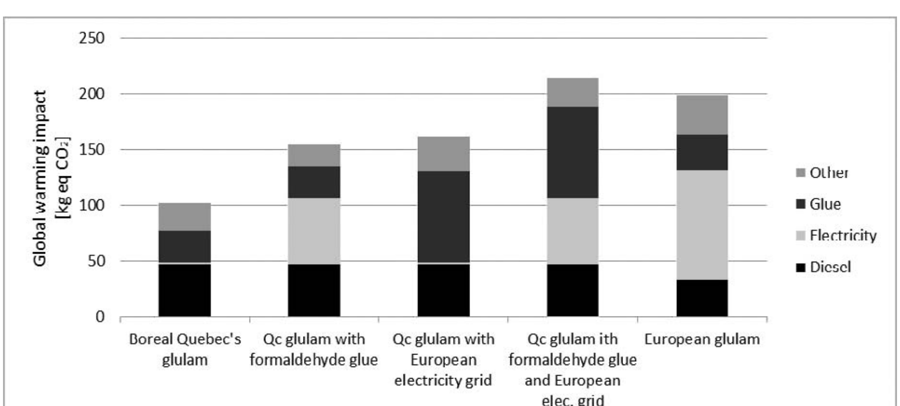

Figure 5.—Sensitivity analyses.

Table 4.—Results of life-cycle analysis (LCA) for glulam from Quebec by economic allocation.

LCA[a]	Economic allocation
Functional unit	m^3 of glulam
Human health (DALY)	3.75E−4
Ecosystem quality (PDF/m^2/y)	105.5
Resources (MJ primary)	2,575
Global warming (kg CO_2 eq)	141.6

[a] DALY = disability adjusted life years; PDF = potentially damaged fraction.

Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). For the other environmental damages, it would also be possible to use other characterization methods like ReCiPe (The Netherlands) or ImpactWorld+, which are being developed to address the needs of regionalized impact assessment covering the whole world. In any case, modeling the impacts of forest occupation and land uses changes will always remain a difficult exercise because different silvicultural practices result in different environmental impacts.

Conclusions

Drying with biomass as an energy source and using most of the tree stem for glulam manufacturing positively affects the performance of Quebec's boreal glulam manufacturing. Results obtained in this study are also strongly affected by the provincial electricity source, namely hydroelectricity. It shows, from an LCA perspective, that there can be some notable advantages to manufacturing products with high energy demand in Quebec with regard to environmental end-point damages. Those considerations are significant enough to give a competitive advantage to Quebec's boreal glulam product, compared with the glulam manufactured in Europe or in the United States, despite the distance and the size of the tree resources.

To our knowledge, this study is the first LCA using primary data pertaining to Quebec's boreal forest. As any LCA, inventory was the most laborious part of this study. It was an opportunity to develop a methodology for collecting forest industry data. Based on this methodology, an online form (https://www.icv-lci.ca) has been created to allow manufacturers to figure their carbon footprint, based on the energy and material needs of their different production stages.

This cradle-to-gate LCA is exclusively environmental. Any considerations of socioeconomic issues, which may also be important, particularly in localities with a strong forest sector, as in the region under consideration in this

Table 6.—Energy consumption by source.

Energy form	Unit	Unit/m^3	GJ/m^3	Repartition (%)
Diesel	l	15.29	0.59	38
Biomass	mtod	0.02	0.3	19.4
Electricity	kWh	114.66	0.41	26.4
Gasoline	l	4.08	0.14	9
Oil fuel	l	2.64	0.1	6.5
Liquefied petroleum gas	l	0.37	0.009	0.6
Jet fuel	l	0.07	0.002	0.15
Total			1.56	100

Table 7.—Energy consumption for 1 m^3 of glulam by processes with related repartition to renewable and nonrenewable energy consumption.

			GJ/m^3	
Department	GJ/m^3	Repartition (%)	Nonrenewable	Renewable
Plantation	0.01	0.69	0.01	0.0002
Forest camps	0.01	1.05	0.01	0
Planning	0.01	0.68	0.01	0
Forest road	0.13	8.46	0.13	0
Harvesting	0.16	10.57	0.16	0
Mechanicals	0.008	0.53	0.008	0
Off-road transportation	0.15	10.01	0.15	0
Extraction	0.5	31.99	0.49	0.0002
Lumber yard	0.01	0.82	0.01	0
Sawmill	0.26	16.92	0.1	0.16
Drying	0.33	21.08	0.03	0.3
Lamination	0.45	28.87	0.2	0.25
Administration	0.005	0.32	0.004	0.001
Manufacturing	1.06	68.01	0.35	0.71
Total	1.56	100	0.85	0.71

Table 5.—Comparison of life-cycle analysis (LCA) results with Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) 2 method of glulam from Quebec, the United States, and Europe.[a]

LCA (TRACI 2 method)	Quebec boreal	USLCI (CORRIM)	ecoinvent
Functional unit	m^3 of glulam	kg of glulam (×517)[b]	m^3 of glulam
Global warming (kg CO_2 eq)	106.2	162.9	224.8
Acidification (H^+ mol eq)	43.6	70.3	77.3
Carcinogenics (kg benzene eq)	0.54	0.074	0.73
Noncarcinogenics (kg toluene eq)	2,650	728	6,563
Respiratory effects (kg PM2.5 eq)	0.24	0.24	0.45
Eutrophication (kg N eq)	0.29	0.03	0.98
Ozone depletion (kg CFC-11 eq)	1.06E−5	2.1E−9	2.2E−5
Ecotoxicity (kg 2,4-D eq)	219	15	674
Smog (g NOx eq)	0.87	0.96	1.17

[a] CORRIM = Consortium for Research and Renewable Industrial Materials; PM2.5 = particulate matter (≤2.5 μm); CFC = chlorofluorocarbon; NOx = mononitrogen oxides.

[b] 517 kg/m^3 is the average density of the Pacific Northwest and Southeast glulam in the CORRIM gate-to-gate life-cycle inventory (LCI) of glued-laminated timbers production (Puettmann and Wilson 2005).

study, were out of its scope. A social LCA of a product like glulam would thus be of further interest.

Acknowledgments

We are thankful to the Chantiers Chibougamau Ltée team who made this assessment possible, in particular Frédéric Verreault, Pascal Ouellet, and Daniel Turcotte. This study was funded by a grant from Natural Science and Engineering Research Council of Canada (NSERC)–Rio Tinto Alcan to J.-F. Boucher and S. D'Amours and by the Carbone boreal program. We also thank the chaire en éco-conseil and the CIRAIG research consortium for their assistance and Sylvie Bouchard and two anonymous reviewers for their comments on earlier versions of the manuscript.

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