Cradle-to-Gate Environmental Life Cycle Assessment of the Portfolio of an Innovative Forest Products Manufacturing Unit

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Manufacturing companies are under pressure from consumers and legislation to reduce their environmental impacts. In some sectors where competition is particularly fierce, the ability to offer a product with a lighter environmental impact than the competition can be useful in significantly increasing market share. The forest industry, which harvests and processes wood, a renewable resource, also aims at being part of this trend towards transparency. Life cycle assessment (LCA) is often used to quantify the environmental footprint of harvested wood products (HWP). Based on a primary data inventory of four years of activity, this study presents an LCA of the portfolio of an innovative forest products manufacturer. The functional unit of that assessment is a cubic meter. A sensitive analysis on an economic allocation was also conducted. Because of loops in the studied system and flow conservation constraint, results of the portfolio LCA was verified using an organizational footprint assessment. From the material flow and the half-life of products, a bottom-up accounting method is suggested for integrating HWP in national greenhouse gas (GHG) inventories.

Keywords: Harvested wood product; Life-cycle assessment; Biogenic carbon; Boreal forest; Construction materials

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INTRODUCTION

Consumers and governments are putting more and more pressure on industry to reduce environmental impacts (Quariguasi Frota Neto *et al.* 2008). This phenomenon can already be observed in many regions of the world. Indeed, product environmental labeling has become a major topic in Europe because consumers want information on the environmental impacts of their purchases. To satisfy this need for transparency, manufacturers must quantify the impacts of their products to document their environmental performance. The ability to offer products with lower environmental impacts can prove to be a competitive advantage, especially in sectors where competition is particularly fierce. In this respect, it has been documented that Quebec producers have the competitive advantage of being able to access hydroelectric energy, with a very low carbon footprint (Wells *et al*. 2011).

The forest industry, which harvests and processes wood, a renewable resource, also aims at being part of this trend toward transparency. The forest industry can potentially benefit from this process of quantifying environmental impacts because, when forests are sustainably managed, its source of raw material is a natural carbon sink resulting from the process of photosynthesis, and wood products stock carbon throughout their lifetime (Karjalainen *et al.* 1999). Since the Conference of Parties in Durban in 2011 (UNFCC, 2012), accounting harvested wood product (HWP) is obligatory for signatory countries of the agreement for the second period of the Kyoto Protocol (2013-2020).

Several studies have shown that HWPs use less energy, and therefore they have a lower carbon footprint than other building materials such as steel and concrete (Sutton 2003; Zabalza Bribián *et al.* 2011), which makes wood products an interesting option in the mitigation efforts against climate change, especially in the construction and energy sectors (Lucon *et al.* 2014). In addition, forest industry manufacturing is a divergent production system, with a large array of coproducts (Gaudreault *et al.* 2011). Recent research on bio-products has contributed to increasing the diversity and the added value of this resource. The production of different forms of lignocellulosic biofuels – also called second-generation biofuels – appeared recently to be technically, though not yet economically, feasible (I. E. A. 2009; Regalbuto 2009; Sims *et al.* 2010). The substitution of fossil fuels by coproducts throughout the life cycle could also help to bring down the carbon footprint of the timber industry (Börjesson and Gustavsson 2000; Petersen and Solberg 2002).

A Life Cycle Assessment (LCA) can be performed at different levels, as presented in Hellweg and Channels (2014). The LCA at the product level is the most common, as is the case in the assessment of the environmental impacts of HWPs (Kunniger and Richter 1995; Adalberth 2000; Sartori and Hestnes 2007; Sathre and O'Connor 2008). The European Commission has been developing a methodology to quantify the environmental impacts of organizations since 2011 (OEF 2012). This methodology, named organization environmental footprint (OEF), is based on the reference life cycle data system handbook (ILCD Handbook) (Chomkhamsri *et al*. 2011). It proposes that the footprint of an organization should be equal to the sum of the footprints of all the goods/services it offers (European Commission *et al.* 2010). That disaggregation at the product level of the total footprint can be more or less difficult depending on the industry type. The diversity of forest products, which do not undergo the same degree of transformation, can make this exercise tricky.

This paper presents a case study on an innovative manufacturer that is distinguished from other forest companies by having a diversified product portfolio. Far from merely making 2x4 wood beams, Chantiers Chibougamau Ltée (CCLtd) was the first to manufacture glued laminated timber (glulam) in Eastern Canada in the early 2000s, and then was the first in Canada to produce cross-laminated timber (CLT). CCLtd have even created an engineering company called Nordic structures to market engineering wood products. The goal of this work is to assess the cradle-to-gate environmental profile, in accordance with ISO 14044 (2006), of each forest product of CCLtd, which amounts to determining the impacts of all wood harvesting and transformation steps. The generated results will then, in future work, supply a multi-criterion optimization model used to identify which scenarios maximize profits and minimize the environmental impacts. This will be a decision support tool for the strategic design of forest products manufacturers. A second objective is to calculate the footprint of the organization, as suggested in the OEF guide (2012). The aim of this exercise is to verify the LCA results of the HWP by summing the environmental profiles of the products in the portfolio. The third objective, presented in the discussion, is to assess the biogenic carbon sequestration potential of the studied product portfolio. This suggested accounting method takes a "bottom-up" approach, relevant for integrating HWP in national GHG inventories.

METHOD

Data Collection

CCLtd was established in Chibougamau (49°55'12.0"N; -74°22'12.0"W), Quebec, Canada, in the 1960s. This study covers only activities located in Chibougamau. It runs the fifth largest sawmill in the province, with an average supply volume per year of close to 1 million cubic meters. CCLtd exploits crownland softwood forests, between 49 °N and 52 °N, which is the northern limit of Quebec's commercial forest. The boreal ecosystem is characterized by the predominance of black spruce (*Picea mariana* (Mill.) B.S.P) (Rowe 1972), a coniferous tree species, which represents 85% of CCLtd production. Black spruce is very resistant to cold and has a short growing season, thus producing small-diameter trees, from 9 to 25 cm at breast height, over a 70- to 120-year regeneration period (Viereck and Johnston 1990). CCLtd continues to have open access to the forest by maintaining the existing network and building new roads. It is an innovative manufacturer generating high-value engineered wood products from small-diameter trees, which is a challenge. It has managed to diversify its products portfolio, differentiating itself from the competition and successfully passing through difficult times, such as the 2008 economic downturn.

Primary data on energy and material inputs as well as land use for wood production was collected by surveys, on-site visits, and multiple interviews with the CCLtd production departments in 2013. All sawmilling and a diversity of remanufacturing operations, including the production of I-joists, glulam, and CLT, are performed on the same site. The primary data spanned from 2009 to 2012, providing enough information to mitigate yearly variations due to natural and economic fluctuations and to calculate standard deviations, allowing uncertainty analyses.

Oriented strand board (OSB) is a key input for the production of I-joists. The OSB manufacturer is located in the north-west of the province of Quebec (Canada), in the boreal forest. The OSB panels are made from trembling aspen (*Populus tremuloides* (Mich)) harvested between the 48th and 52nd North parallels. Because of a lack of relevant LCA data on OSB production in Quebec, primary data were collected from the OSB supplier in 2012. An LCA on OSB has been performed in Europe by Bennett *et al.* (2009) and an inventory in 2005 by Kline in North America (Kline 2005). The latter used the USLCI database, a North American database, but the European database, *ecoinvent*, was privileged.

Data on background processes, *e.g.*, energy production, infrastructure, vehicles, machines, and adhesives, were obtained from available LCI databases. The *ecoinvent* version 2.2 database (Hischier *et al.* 2010) was preferred to the USLCI database because it is more complete and presents uncertainty data for the included process flows. As mentioned by Hellweg and Canals (2014), regionalization of LCAs makes them more relevant and reduces uncertainty. That is why efforts have been made to adapt the database as much as possible to the North American and Quebec contexts. The Quebec grid mix (MERN 2012a) and the crude oil mix (MERN 2012b) (obtained from the Quebec ministère de l'énergie et des ressources naturelles (MERN) website) was used for the foreground processes. The North American grid mix (EIA 2012) (obtained from the U.S. Energy Information Administration website) was used for the background processes, as for the adhesive production. Other changes have also been made to the original European database. For example, a dataset for the pickup truck used by the wood products company workers was created based on a car dataset in the *ecoinvent* database, *i.e.*, the weight, fuel consumption and road use parameters were modified accordingly.

To take into account land use effects, biogenic carbon content, and calorific value of the wood resource, the European model for softwood available in the *ecoinvent* database v2.2 (Hischier *et al.* 2010) was adapted to the specificities of black spruce in the Quebec boreal forest.

For CO_2 uptake, the original 49.9% w/w carbon content (based on dry mass), including bark (~10% total volume of trees) was not changed, and a density (specific gravity) of 406 $kg.m^{-3}$ was assumed (Jessome 1977). For modeling the land use change from natural forest to extensive forest use, an average of 70 year mature age-classes was used (Sansregret and Blanchette 2003).

The average annual growth rate is about 1.43 $m^3.ha^{-1}.year^{-1}$ (CRRNTSLSJ 2011), making the average harvestable volume per hectare to be 100 $m^3.ha^{-1}$. In addition, for modeling the land occupation, a full regeneration cycle of black spruce tree is 120 years long (Johnson 1996).

Functional Unit

The functional unit, describing quantitatively the service being provided by the studied product system, serves as the reference to which all inputs and outputs are mathematically related, and it is defined here as “the transformation of one cubic meter (m^3) of harvested wood in Quebec between 2009 and 2012”. However, results are presented per solid m^3 of products for each of the coproducts, based on over-dry density or volume conversion factors.

The system includes all HWP manufacturing coproducts (bark, sawdust, chips, green wood, dry wood, planed wood, flange, I-Joist, glulam, CLT, and shavings), as long as these are considered to be valuable and used.

In conformity with common practice in sawmills and in accordance with ISO standards, coproduct allocation was calculated on a volume basis, as suggested by products category rules (PCR) for the wood sector (Institut Bauen und Umwelt e.V. 2009; The Norwegian EPD Foundation 2013). This is in compliance with ISO 14044 (2006), which states that, where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them.

System Boundaries

The cradle-to-gate system boundary encompasses all stages, from wood resources harvesting to HWP manufacturing, including facility, materials, and energy inputs as shown by the dotted line box in Fig. 1.

As presented in Fig. 1, the administration and maintenance services are taken into account in the inventory. The administration consumes mainly electricity and fuels, including jet trips. Maintenance consumes various products such as oils or metal but mostly fossil fuel. As these services are common to all activities, the inputs have been redistributed to production activities on volume basis.

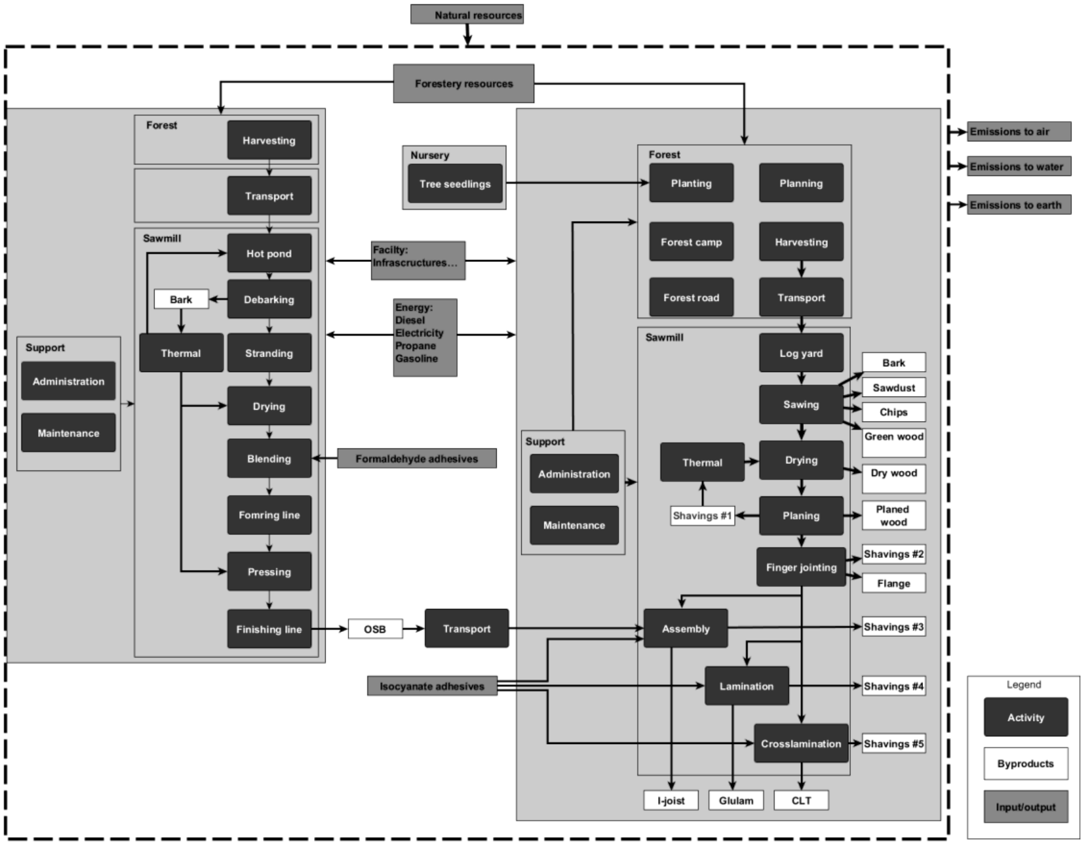

Fig. 1. System boundaries of cradle-to-gate HWP manufacturing system, included

Activities Description

As previously mentioned, the wood is harvested from Quebec's boreal region. Some particularities of the northern forest make harvesting operations quite different from what happens in the southern mixed forest. There are two major phases of HWP production. The first is the primary material extraction. This phase occurs upstream in the forested area and can be broken down into six steps. The second, the downstream phase, is log transformation and HWP manufacturing at the factory. All activities are described in the next table. Because OSB and other HWP production do not have much in common, their manufacturing activities are described separately.

Table 1. Activities Description

Extraction	The five activities of the extraction step can be broken down into other subactivities. For more details on forest operations, please refer to the "Manuel du forestier" edited by the Quebec Ministry of Natural Resources.	
	Plantation	To ensure sustainable regeneration, harvested areas in the Quebec public boreal forest are required by law to be reforested. Consumption data are extracted from an LCA on management of Quebec's boreal forest (Gaboury *et al.* 2009).
	Forest Road	To access the resource, the forest industry has to build and maintain forest roads. These two processes consider the energy

		consumed by construction machines as well as the manufacturing of their equipment. Land use of forest road is not taken into account for three reasons. Winter road impact on land use is difficult to quantify. A large number of roads have to be closed to respect the FSC standard. Surfaces of permanent roads are negligible compared to the harvesting surfaces.
	Forest Camps	Harvesting areas are rather far from towns, so harvesting requires accommodating workers in housing. Only the fuels consumed are taken into account in the model.
	Harvesting Planning	Every harvest is planned by a team of forest engineers. This requires periodic trips to the harvesting area.
	Harvesting	Consumption data covers all harvesting activities of softwood and hardwood. Hardwood harvesting, for OSB production is realized after softwood extraction. That means harvesters go into softwood harvest areas, then harvest hardwood trees. They use the same facility as for softwood harvesting, as the forest road. In this study, hardwood harvesting is not practiced in the same area as softwood. So 15% of the softwood forest road is allocated to forest road building and maintenance for hardwood harvesting, which represents hardwood volume on total timber extraction.
	Non-Paved Road Transport	Log transport between forest operations and the mill is represented by the truck transportation dataset from the *ecoinvent* database v2.2 (Hischier *et al.* 2010), but the flows associated with road use were adapted to represent the specific context.
Manufacturing		
OSB production	After harvest and transportation from forest, whole logs are hauled to the mill's wood yard, then sorted. OSB manufacturing is separated into 8 activities.	
	Hot pond	Logs are soaked in hot water, to clean them and to remove ice during winter, and are then transported to the mill via a jack ladder.
	Debarking	Drum debarkers are used to remove bark from logs. Bark is burned in the boiler as fuel to meet the mill's energy demand. Hot oil is used for heating the pond, drying strands and at the press.
	Stranding	Logs are ground into six-inch long strands. Then strands are deposited into two wet bins.

	Drying	Strands are dried to two distinctive moisture contents. At the pressing process, the inner layers are not in contact with the hot press plates, unlike the exterior layers. This is the reason why humidity is not the same for strands deposited in exterior and interior layers.
	Blending	Strands are blended with formaldehyde adhesives and wax, the latter of which improves the panel's resistance to water.
	Forming line	Strands go through the forming line where 4 layers are formed. Inner and exterior layers are cross-directional, which improves mechanical resistance.
	Pressing	A 12-stage press operates discontinuously to receive mattresses made of 4 layers. Strand mattresses are pressed under intense heat and pressure to form a rigid, dense structural panel of oriented strand board (OSB). Oil that is used as hydraulic fluid is heated to an approximate temperature of 210°C in the press plates to heat the panels before moving back to the bark boiler for further heating.
	Finishing Line	Panels are cooled, cut to size, and stacked in bundles ready for shipping. Different thicknesses and quality, such as water resistance and strength, are identified by the color code on the flanks.
Initial Transformation of Logs into HWP at the Sawmill	The initial transformation of logs into green wood, dry wood, and planed wood occurs at the sawmill. This activity generates coproducts such as bark, sawdust, and chips. Typically, a sawmill operation includes debarking, sawing, drying, and planing. Some diesel fuel is consumed for the loader which manipulates the wood board; otherwise the energy consumed is almost entirely in the form of electricity, which has a very low carbon emission intensity in Quebec due to the high proportion (on the order of 99%) of hydroelectricity in the grid mix. The lack of data resolution does not allow the disaggregation of the debarking and sawing activities. Therefore, inputs and outputs are allocated, based on volume, proportionally to these products. Data allowed a separate accounting of the drying process, which is useful for calculating the energy consumption associated with each coproduct.	
	Lumber Yard	Upon arrival, the off-road truck is weighed, and logs are unloaded in the lumber yard where they are manipulated and selected according to the demand. This stage uses diesel combustion in building machines available in *ecoinvent*. Logs are subsequently transported to the sawmill.
	Sawmill	Logs are debarked, generating the bark coproduct. Logs are then processed to produce the green boards, generating chips and sawdust. In the studied sawmill, sawing processes are automated and optimized to maximize output value.

	Drying	The majority of the thermal energy required for drying is generated by burning shavings, although light fuel oil is still used as back-up.
	Planing	After drying, planing sizes the wood to commercial dimensions. This process generates shavings, referred to in Fig. 2 as shavings #1. Only electrical energy is used at this step.
Secondary Transformation of HWP	The secondary processing includes finger jointing, which produces I-Joist flange material that is subsequently assembled with OSB to produce I-Joists; lamination and cross lamination, which generate glulam beams and CLT panels; and machining of the glulam beams and CLT panels to produce a finished product, to be assembled on a construction site.	
	Finger Jointing	Only the highest quality boards, machine stress rated (MSR) lumber grade, is sent to the second transformation plant. The first activity is finger-jointing to produce the required length, which generates shavings, referred to as shavings #2.
	Assembly	Assembly is the process of gluing the flange material with the OSB panel. There are different sizes and quality grades, referred to generically as “I-joist” in this study. Cutting to commercial length generates sawdust, referred to as shavings #3.
	Lamination	Finger jointed lumber is then edge glued. Once cured, these edges glued boards are faces glued according to the required dimensions. All gluing steps use isocyanate adhesives and are dried by microwave. To make the finished product, the last step is machining by a 5-axis CNC to machine the glulam timber exactly to the architectural plan specifications. Scrap cuttings from glulam are referred to as shavings #4.
	Cross-Lamination	Alternatively, finger-jointed lumber can also be edge glued into large panels. These large boards are then cross-laminated one over the other. This operation is repeated 3, 5, or 7 times, to constitute cross-laminated timber (CLT) panels, depending on the requested use. Panels are then machined to accommodate doors and windows. Scrap cuttings from CLT production are referred to as shavings #5.

Flow of Material in Factory

In the Canadian wood products sector, most coproducts are sold, the rest being used on site (Meil *et al.* 2009). The allocation of the lumber company’s inputs and outputs to the different coproducts is volume based. Figure 2 presents the share of the different coproducts, on a volume basis, of the total production for years 2009 to 2012. Debarking is included in the sawing activity and its product, *i.e.*, the bark, represents almost 10% of the total volume. This bark is sold to an electricity producer. The most important product, representing 53% of the total volume, is chips, sold for pulp and paper production. Chips also include almost 10% of shavings generated (not shown in Fig. 2). Just over 20% of the processed logs are transformed into a light frame softwood, mostly used for residential construction. Two percent is used for the production of solid wood products, glulam and CLT, for the nonresidential construction sector.

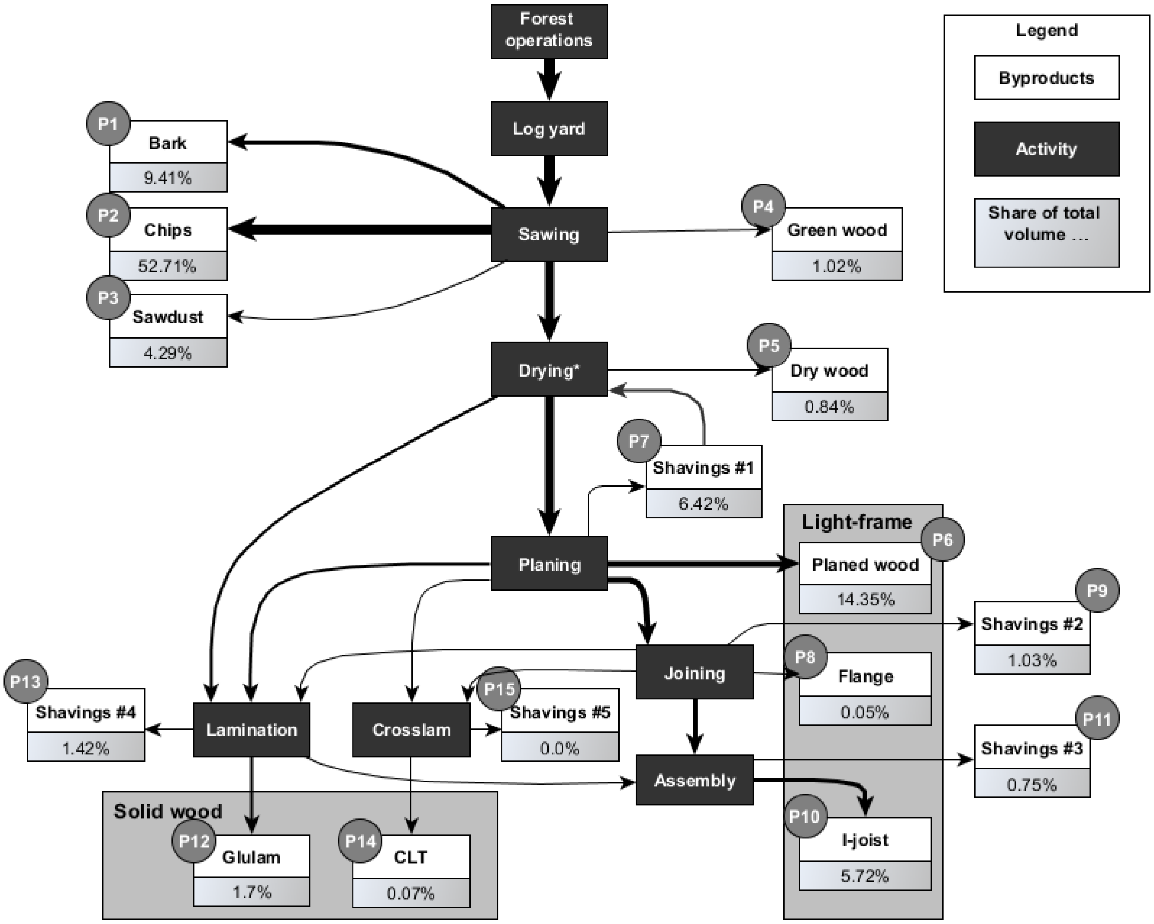

Fig. 2. Flow of material
* Products after dying are slightly denser because of some retraction; however, no adjustments to the volumes calculations were made to account for this.

LIFE CYCLE IMPACT ASSESSMENT

A slightly modified version of the European impact assessment method, IMPACT 2002+ V2.1 (Jolliet *et al*. 2003; Humbert *et al*. 2005) was used. Impact assessment analysis was conducted with two other methods, TRACI and ReCiPe, to test the robustness of the conclusions obtained with IMPACT 2002+. The life cycle inventory and impact assessment calculations were performed with the LCA software SimaPro 7.3.3 PhD version developed by *Pré Consultants* (www.pre.nl).

Results and Interpretation

The results for the four damage categories are presented in Figs. 3 to 6, per one cubic meter of outputted HWP. As can be seen in the different figures, because of the approach taken for allocation, all coproducts generated by the same activity show the same score.

Often in LCA, inventory data uncertainty is determined using a data quality pedigree matrix (Weidema and Wesnaes 1996) and basic uncertainty factors (Frischknecht *et al.* 2004). That approach was used to determine uncertainty of infrastructure and equipment data. Also, the collection of four years of activity allowed determining the variability and uncertainty on the primary process data. Weighted averages and uncertainty are calculated on the basis of the variability of the production as well as glue and energy consumption. Uncertainty of results was estimated through performing Monte Carlo analysis using 1,000 simulation iterations in SimaPro. The results of that uncertainty analysis are represented by the error bars in the next figures.

Table 2. LCA Results by Activities and the Portfolio of Products per Cubic Meter of Output Basis

Activity	HWP	**Climate change** (kg CO_2 eq.)	CV	**Ecosystem quality** (PDF.m^2.yr)	CV	**Human health** (DALY)	CV	**Resources** (MJ)	CV
Harvesting + Sawing		44.40	9%	310.88	24%	7.93E-05	25%	681.62	10%
	P1-Bark	**44.40**	**9%**	**310.88**	**24%**	**7.93E-05**	**25%**	**681.62**	**10%**
	P2-Chips	**44.40**	**9%**	**310.88**	**24%**	**7.93E-05**	**25%**	**681.62**	**10%**
	P3-Sawdust	**44.40**	**9%**	**310.88**	**24%**	**7.93E-05**	**25%**	**681.62**	**10%**
	P4-Green wood	**44.40**	**9%**	**310.88**	**24%**	**7.93E-05**	**25%**	**681.62**	**10%**
Drying		0.72	0%	0.08	0%	2.43E-07	12%	11.11	9%
	P5-Dry wood	**50.82**	**8%**	**350.21**	**21%**	**8.96E-05**	**22%**	**780.71**	**9%**
Planing		0.18	0%	0.77	0%	2.44E-07	41%	6.08	33%
	P6-Planed wood	**51.00**	**8%**	**350.98**	**21%**	**8.98E-05**	**22%**	**786.79**	**9%**
	P7-Shaving 1	**51.00**	**8%**	**350.98**	**21%**	**8.98E-05**	**22%**	**786.79**	**9%**
Jointing		9.10	77%	2.11	47%	6.45E-06	109 %	265.78	100 %
	P8-Flange	**60.10**	**13%**	**353.08**	**21%**	**9.63E-05**	**21%**	**1 052.51**	**26%**
	P9-Shaving 2	**60.10**	**13%**	**353.08**	**21%**	**9.63E-05**	**21%**	**1 052.51**	**26%**
OSB		124.15	19%	395.95	8%	2.46E-03	8%	7 355.21	7%
Assembly		15.19	26%	3.16	32%	2.33E-05	43%	468.32	39%
	P10-I-joist	**66.11**	**23%**	**333.87**	**23%**	**6.35E-04**	**14%**	**2 484.38**	**17%**
	P11-Shaving 3	**66.11**	**23%**	**333.87**	**23%**	**6.35E-04**	**14%**	**2 484.38**	**17%**
Lamination		60.44	28%	9.47	32%	9.47E-05	42%	1 885.29	38%
	P12-Glulam	**112.01**	**15%**	**359.97**	**21%**	**1.85E-04**	**27%**	**2 688.23**	**27%**
	P13-Shaving 4	**112.01**	**15%**	**359.97**	**21%**	**1.85E-04**	**27%**	**2 688.23**	**27%**
Cross-Lamination		20.75	14%	0.54	0%	1.26E-05	16%	494.21	14%
	P14-CLT	**77.21**	**8%**	**352.77**	**21%**	**1.06E-04**	**19%**	**1 440.47**	**13%**
	P15-Shaving 5	**77.21**	**8%**	**352.77**	**21%**	**1.06E-04**	**19%**	**1 440.47**	**13%**

Human health

The Human health damage indicator is expressed in disability-adjusted life years (DALY), a metric used by the World Health Organization (Humbert *et al.* 2005) and adapted to LCA by the impact assessment method developers. The scores obtained range from 7.89E-05±2E-05 to 1.85E-04±4.7E-05 DALY per cubic meter, the highest score for the glulam and shavings coming out of the lamination activity. As mentioned, lamination of small pieces of wood consumes a large quantity of isocyanate adhesive. This is what explains the glulam's score for this damage category. For products that do not contain adhesive, the main contributor is diesel fuel, mostly from its combustion (via the respiratory inorganics impact category) rather than from its production (crude oil extraction and refining).

Ecosystem quality

The Ecosystem quality indicator is expressed as the potentially disappeared fraction of species on a certain area over a period of time (PDF.m².y). The scores obtained range from 248±84 and 356±75 PDF.m².y. The largest contributor (95% for all HWP) is the land use associated with the wood resources, the land occupation during forest growth. Shavings, used as a thermal energy source for the drying operation, explain why dry HWP shows a higher score. The lower scores for I-joists occur because they are composed of both softwood and hardwood: though harvesting of both woods are done in the same territory, hardwood is more productive than softwood and hence has a lower land occupation indicator result.

Damages to ecosystem quality are presented here to compare HWPs between them, and as they are necessary to generate the subsequent multi-criterion optimization model. However, they should not be used in another context because they do not reflect the Quebec boreal forest context.

The characterization factors used are those for Europe, where forestry practices are quite different. As suggested by de Baan *et al.* (2012), regionalized characterization factors are required because biodiversity has an uneven geographical distribution and its response is non-uniform to land use. Unfortunately, characterization factors have not yet been developed for the Boreal Forest and Taiga biome.

Global warming

The production of 1 m^3 of HWP in this cradle-to-gate assessment emits a total between 44.3±3.6 and 111±18 kg of CO_2 equivalent. Glulam is the HWP that has the largest global warming damage potential. The most important contributor is the manufacturing of adhesives, with 47 percent of GHG emissions because of the lamination activity. The consumption of diesel fuel is also important, with 41 percent of emissions. The second-highest HWP score is the production of I-joist because of consumption of OSB, whose emissions from production and transport rise to 264 kg of CO_2 equivalent per m^3. For products which do not contain adhesive, diesel fuel combustion is by far the biggest contributor.

Quebec hydroelectricity being almost carbon neutral, according to the hydropower model in *ecoinvent*, its usage in sawmills does not affect the GHG balance significantly. These results are consistent with the conclusion of previous LCA on glulam from Quebec's boreal forest (Laurent *et al.* 2013).

Resources

The resource damage category is the sum of non-renewable energy and mineral extraction, expressed in MJ of primary non-renewable energy. The production of one cubic meter of HWP consumed between 682±68 and 2688±720 MJ of non-renewable energy. A direct relationship between the climate change and nonrenewable energy indicators is observed as diesel fuel, through its crude oil extraction this time is again the biggest contributor. The highest total energy consumption is associated with glulam because of the consumption of adhesives. I-joists are also a major consumer of energy, also because of the use of adhesives. The transport of OSB between the two production locations also has a contribution of 5% to this damage category.

It seems difficult to reduce the environmental impacts of these HWPs, mostly because the electricity grid in Quebec has a very low carbon intensity. One option would be to convert forest machinery and transport trucks to biofuels. It would also be possible to optimize the flow of materials. This method is used to minimize production costs and maximize profits (Shahi and Pulkki 2013). By accounting for both the relative environmental and economic performance of the HWP in a multi-criterion optimization model, one could identify strategies or portfolios that both minimize environmental impacts while maximizing profits (Bernier 2011; Čuček *et al*. 2011; Cerri *et al*. 2013; Kostin 2013; Rivallain 2013). There is yet no publication applied to forestry, to our knowledge.

Sensitivity Analysis of Allocation Approach

The results presented previously are based on a volume allocation. To verify their robustness, a sensitivity analysis was performed using economic allocation. Indeed, the type of distribution of incomings influences the results. This is especially true in divergent processes that generate several co-products.

The economic allocation is based on the company's revenues. For privacy reasons, it is not possible to have the accounting data. Profits were calculated based on the production volume and average sale prices on the North American wood markets. These prices are available on brokerage sites such as RISI (www.risiinfo.com). It is possible to make a mistake by not applying the economic allocation to the right point (Ardente and Cellura 2012). Because this is a gate-to-gate LCA, distribution impacts are not considered. These are the market prices that were used and not the consumers buying price.

Solid wood products, such as glulam and CLT, are high-value-added HWP. While solid wood production represents 2% of the volume of CCLtd activities, it corresponds to 15% of GHG emissions using economic allocation. Another interesting product is chips, which are used by the pulp and paper industry. Chips, which account for 50% of the total volume, are responsible for 43% of GHG emissions of the manufacturer, while the paper industry considers the same chips as a waste from the sawmill.

In view of the variation in results depending on the allocation factor, a sensitivity analysis was performed on economic revenue of the whole HWP portfolio. Thus, the damages of 1 m^3 of each product of CCLtd's portfolio were recalculated by economic revenue allocation to assess the changes. To be more relevant, the results observed in economic allocation were placed next distribution by volume, Fig. 3.

The average selling price of each product of the portfolio was calculated for the period of the study from various sources, such as databases on the North American market that was provided to us by the Ministry of Natural Resources and Wildlife of Quebec.

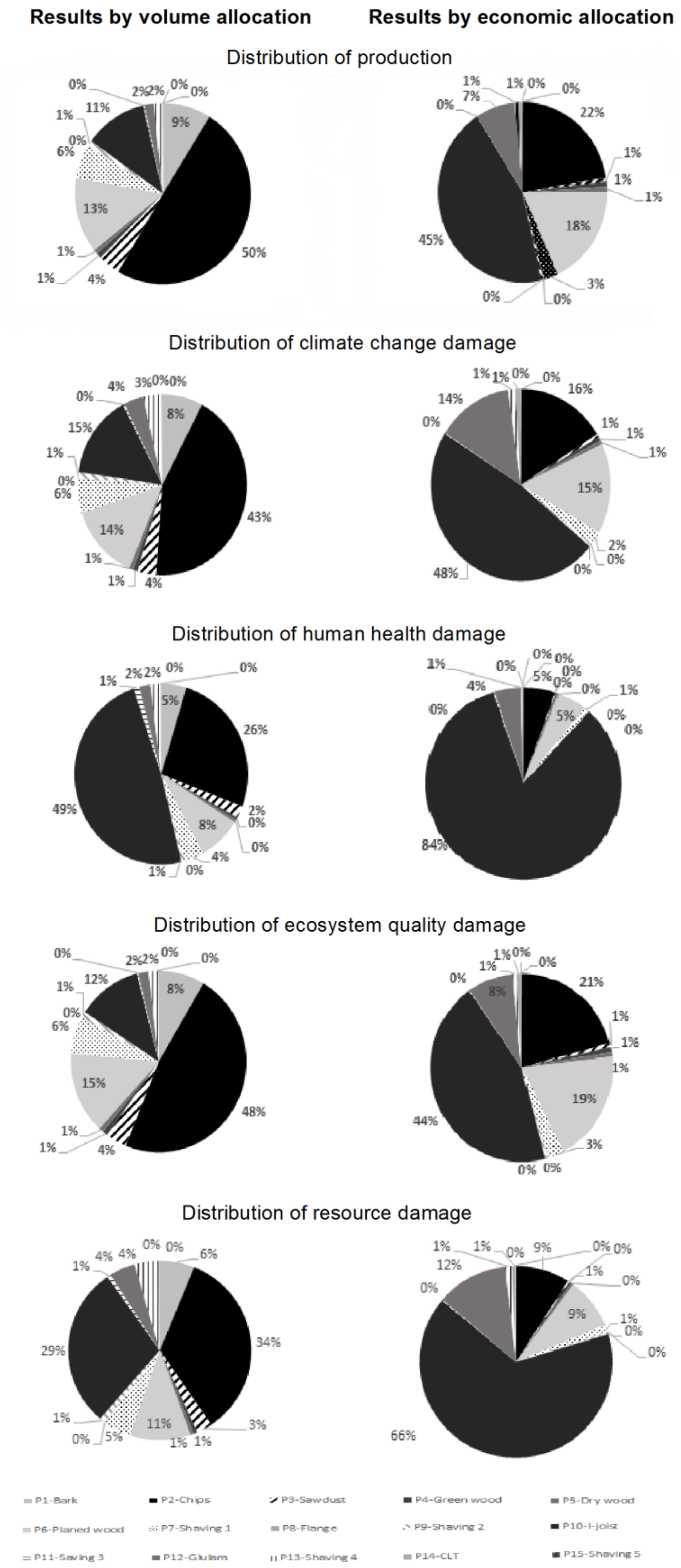

Fig. 3. Comparison between volume and economic allocations of the portfolio of HWP

It is interesting to note that the portrait of environmental damages is radically altered by an economic allocation. The impact of chips, planed wood, and I-joists becomes unbalanced. Because of the low value of chips, impact scores are on average divided by two when using economic allocation, while the opposite effect is seen for I-joist and other high value-added products. Despite the low-volume production of glulam and CLT, the economic allocation makes the damage caused by these two products more important products than with the volume allocation. On intermediate products such as planed wood, the choice of allocation approach does not make a significant difference, as expected.

Organization Assessment

The results for the portfolio of goods were compared with those for the organization. As mentioned in the introduction, this exercise can be difficult for a divergent industry such as the forest industry (Gaudreault *et al.* 2011). Additionally, the use of a part of the generated shavings as an energy source for the drying activity creates a loop in the system.

Production of 3,781,934 cubic meters of HWP, over the four-year period covered by the analysis, resulted in emission of slightly less than 206,000 tons of CO_2 eq. This matched the amount calculated for the organization over these four years of activity (0.01% difference). The results for the other three damage categories showed less than a 0.25% difference.

The comparison between the results for the entire portfolio of goods and for the organization serves as a validation step. Indeed, the SimaPro LCA software is able to handle a loop in the system when assessing only one product. However, when combining the individual assessments for each coproduct making up the portfolio of goods, this loop creates discrepancies in the overall material flows, notably the amount of roundwood. An activity-based approach, using a spreadsheet calculation tool, was then used, which made it possible to obtain consistent results.

DISCUSSION

Biogenic Carbon Sequestration Potential of HWP

Carbon sequestration is the process of capturing carbon from the atmosphere. Photosynthesis converts atmospheric CO_2 into solid matter. Because this carbon sequestration is from a biological process, the carbon in vegetal materials is called biogenic carbon. Wood is made up of approximately 50% biogenic carbon on a dry mass basis (Ter-Mikaelian *et al.* 2008). When trees are harvested and converted into a wood product, this results in carbon sequestration in HWP. This storage lasts for the lifespan of the products. Afterwards, the destiny of this carbon depends on the end-of-life of the HWP.

Sustainable forest management can contribute to global warming mitigation efforts through the increase in forest carbon stocks and increased carbon storage in HWP (Nabuurs *et al.* 2007). When looking at the Canadian forest carbon budget, the forest carbon balance is almost neutral during the period covered by the study (Environment Canada 2015). It must be remembered that this balance does not integrate sequestration by the HWP. Moreover, the forest carbon emissions are primarily a result of natural disturbances such as fires or insect epidemics (Stinson *et al.* 2011). For further information on the calculation method of forest carbon and for more details consult the report called “The Carbon Budget of the Canadian Forest Sector” (Kurz 1992).

The potential for carbon sequestration in HWP produced by a logging company can be estimated through the flow of material and using a prediction of the use and lifespan of wood products. Products from the manufacturer's portfolio were aggregated in HWP categories, or families of product, identified in Chapter 12 of the Guidelines for National Greenhouse Gas Inventories (IPCC 2006). As shown in Fig. 4, the categories of pulp & paper, containing chips and shavings not used as fuel on the site, represent the largest part (61%) of the production. The bark and shavings used for energy represent 14% of the volume. The construction materials are classified into two distinct categories, light frame and solid wood products, because their use and useful life differ. These represent 23% and 2% of the total value, respectively.

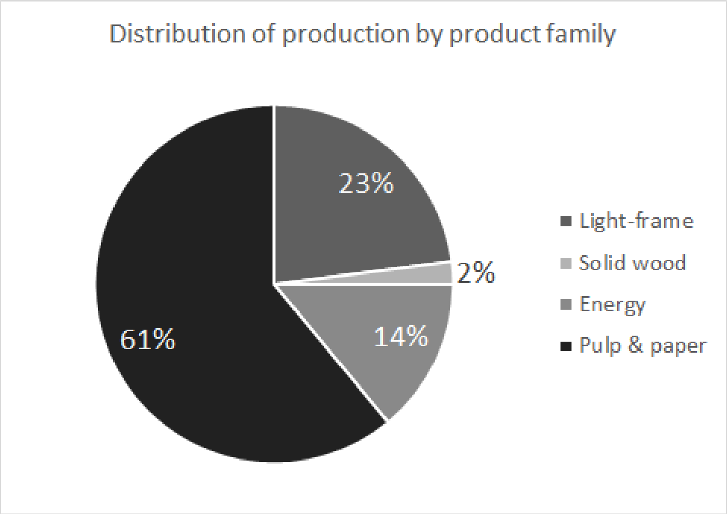

Fig. 4. Distribution of production in volume by harvested wood products categories

From this distribution, the biogenic carbon sequestration potential of the sawmill production can be determined on a per m³ basis. The lifetime of harvested wood products (HWP) is estimated from the decay process of the products (Skog and Nicholson 2000). The half-life of each category of HWP was determined by Skog and Nicholson (2000) and is available in Table 3A.1.3 of the LULUCF Sector Good Practice Guidance (IPCC 2003). If the biogenic carbon was considered, the manufacturer has sequestration of 1.5 tons of carbon per m³. Results of the calculation are presented in Table 3.

Table 3. Calculation of Biogenic Carbon Sequestration by HWP

	Half-life in use (year) *	Sequestration (tC.m^{-3}.y^{-1})
Energy	0	0
Pulp & paper	2	0.247
Light frame	23	1.073
Solid wood	45	0.182
Total		1.504

* Source: Skog and Nicholson (2000) in IPCC GPG LULUCF (2003)

In 2001, at the United Nations Climate Change conference in Durban (COP 17), an agreement was reached on issues related to forest products accounting. The parties may declare credits for HWP, using a production approach (PA). Obviously, the data must be transparent and verifiable. This approach does not allow the recognition of imported wood products. Finally, although the HWP can now be taken into account, countries are still subject to the terms of the new 3.5% "cap" (Ellison *et al.* 2013). To achieve this balance, the data on flows of material of forest companies can be compiled by the companies themselves or by external agencies. Repeating this exercise for different forests, sawmills, from different ecosystems across the country, would draw a realistic picture of the production of HWP in Canada. Supplemented by export statistics would account for the impact of HWP in the national inventory of GHG emission.

To estimate the effects of the substitutions, LCA results of competitors' products are used (Smyth *et al.* 2014). To be fair; the impact on climate changes of HWP should be subtracted even if it affects just a bit of the end result. Indeed, in this LCA, the weighted average of anthropogenic emissions are only 50.7 kg CO_2 per m^3. By subtraction their anthropic emissions on the biogenic carbon in HWP, the carbon sequestration is 5.469 t CO_2 eq. per m^3.

CONCLUSIONS

1. This article presents the life cycle assessment of all products in the portfolio of an HWP manufacturer. A volume allocation was used as suggested by the forest sector product category rules (PCR) (Institut Bauen und Umwelt e.V. 2009; The Norwegian EPD Foundation 2013). Results, with uncertainties, are shown in Table 2. The strong dependence of results on the chosen allocation method is demonstrated through a comparison of results with those obtained when using economic allocation, as shown in Fig. 3.
2. The LCA of a portfolio can serve various purposes. First, it can allow companies to quantify the environmental organization footprint while determining the impact of each of their products individually, for marketing or strategic management. Portfolio approach makes the analysis of hot spots and products easier. Although an individual LCA can afford to generate environmental product declarations (EPD), a portfolio assessment can help make publications more systematic.
3. The analysis of the product portfolio can also be useful to determine the overall environmental impacts of the company. This provides more information than does only performing an LCA of the organization. Eventually, this may be relevant to identify strategies to reduce environmental impacts of each product or the organization as a whole.
4. In view of the relatively low environmental impact of harvesting and processing of wood products, it seems quite difficult to reduce it significantly. This is even truer in the province of Quebec, where electricity has a low carbon intensity. Gains are still possible by using LCA results in an optimization model. This would permit identifying the least harmful material flow for the environment. In a prospective approach, one could also model new technologies for generating new HWP that could reduce the overall environmental impacts.

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