

## Research Article

**Life Cycle Assessment of North American Laminated Strand Lumber (LSL) Production**

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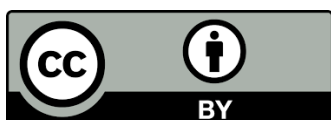
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**Abstract**

Raw materials for buildings and construction account for more than 35% of global primary energy use and nearly 40% of energy-related CO<sub>2</sub> emissions. The Intergovernmental Panel on Climate Change (IPCC) emphasized the drastic reduction in GHG emissions and thus, wood products with very low or negative carbon footprint materials can play an important role. In this study, a cradle-to-grave life cycle assessment (LCA) approach was followed to quantify the environmental impacts of laminated strand lumber (LSL). The inventory data represented North American LSL production in terms of input materials, including wood and resin, electricity and fuel use, and production facility emissions for the 2019 production year. The contribution of cradle-to-gate life cycle stages was substantial (>70%) towards the total (cradle-to-grave) environmental impacts of LSL. The cradle-to-gate LCA results per m<sup>3</sup> LSL



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were estimated to be 275 kg CO<sub>2</sub> eq global warming, 39.5 kg O<sub>3</sub>eq smog formation, 1.7 kg SO<sub>2</sub> eq acidification, 0.2 kg N eq eutrophication, and 598 MJ fossil fuel depletion. Resin production as a part of resource extraction contributed 124 kg CO<sub>2</sub> eq (45%). The most relevant unit processes in their decreasing contribution to their cradle-to-grave GW impacts were resource extraction, end-of-life (EoL), transportation (resources and product), and LSL manufacturing. Results of sensitivity analysis showed that the use of adhesive, consumption of electricity, and transport distance had the greatest influences on the LCA results. Considering the whole life cycle of the LSL, the final product stored 1,010 kg CO<sub>2</sub> eq/m<sup>3</sup> of LSL, roughly two times more greenhouse gas emissions over than what was released (493 kg CO<sub>2</sub> eq/m<sup>3</sup> of LSL) from cradle-to-grave. Overall, LSL has a negative GW impact and acts as a carbon sink if used in the construction sector. The study results are intended to be important for future studies, including waste disposal and recycling strategies to optimize environmental trade-offs.

### Keywords

Engineered wood products; green buildings; laminated strand lumber; environmental impacts; life cycle assessment; environment product declarations

## 1. Introduction

The world is facing severe challenges from climate change and resource scarcity due to exponential growth in population and their rising standard of living [1]. Raw materials for buildings and construction account for more than 35% of global primary energy use and nearly 40% of energy-related CO<sub>2</sub> emissions [2]. Wood has been an important renewable resource catering to the needs of human civilization in different forms. The consumption of renewable energy in the year 2020 has reached a record share of 12% in total energy consumption in the U.S, and 20% of this consumption was from wood and waste energy [3]. The Intergovernmental Panel on Climate Change (IPCC) emphasized the need for a drastic reduction in GHG emissions. Thus, wood products with low or negative carbon footprint materials can play an important role. The use of wood-based products in the construction sector is a significant source of environmental improvement and economic gain [4, 5]. The environmental impacts of wood products have been estimated to be lesser than conventional equivalents in the construction sector [5, 6]. In response to the increasing demands for sustainable buildings, the construction sector has guided the quest for many functional innovations in wood-based products [7]. These innovations have centered on an overarching plan of using the forest resources to their maximum potential to produce low-carbon-footprint construction products. For buildings, the carbon stored in wood products remains fixed for a very long time [8]. A global market for a wide group of engineered wood products (EWPs) has emerged in the past several decades to better utilize the available wood source, including mill residues and small-diameter trees. They are so named because they are engineered to exhibit desirable mechanical and physical properties while efficiently using wood. Resource efficiency for EWPs is based partially on adhesive bonding technology applied to different elements produced as co-products (wood chips, strands, flakes) in primary wood processing [9]. EWPs can form larger and complex structural sections, reducing the natural flaws along with enhancing dimensional strength

and homogenous traits [10]. One category of such products is structured composite lumber (SCL) made from wood strands of different tree species and commonly used in structural applications [11]. SCLs include laminated veneer lumber, laminated strand lumber, oriented strand lumber, and parallel strand lumber.

Laminated strand lumber (LSL) is an important member of the family of SCL [12]. They are made of wood strands pressed together and bonded with adhesive into billets (large, densified mats) which are then cut into different sizes. The largest industrial production of LSL occurs in North America (333,780 m<sup>3</sup> in the year 2019); two total manufacturers, one in the U.S. and the other in Canada [13]. LSL is produced from small-diameter trees (with a high length to thickness ratio), which are unsuitable for solid wood building materials like framing lumber [14]. The most used wood species for LSL production in North America are a mixture of aspen (*Populus tremuloides*), yellow birch (*Betula alleghaniensis*), and silver (soft: *Acer saccharinum*), and sugar maple (hard: *Acer saccharum*).

The uniform engineered properties of LSL have been useful in various applications, such as frames, studs, headers, and beams. The production and use of LSL and SCL, in general, have progressively increased mainly because of the low energy inputs and emissions when compared to other non-wood construction materials [9, 15, 16]. Moreover, considering that carbon sequestered through the forests and carbon dioxide emissions saved from avoiding using other construction materials (steel and concrete) would make them suitable for alleviating impacts from climate change [10, 17, 18]. The use of wood products in the construction sector has estimated a sink of 441 million tonnes CO<sub>2</sub> eq./year in 2030 [6]. Up to 14 - 34% CO<sub>2</sub> emissions and 12 - 19% fossil fuel usage would be avoided by efficient use of sustainably grown forest resources [4].

Along with the increasing interest in using EWP (LSL in this study) in construction, interest in assessing their sustainability has also increased. Tools like life cycle assessment (LCA) have attained high popularity for assessing the environmental impacts of wood products [19]. LCA-based information is integral to decision-making and continuous improvement in the existing products over time [20]. The findings of LCA studies in the construction sector have become increasingly important in obtaining green building certifications, environmental product declarations (EPDs), and informing the public and policymakers [16, 20, 21]. Because of the advent of Environmental Preferential Purchasing (EPP), documenting the environmental performance of building products using tools like LCA has become a widespread emergent global trend [5, 22]. In general, the manufacturing of SCL has some process inputs in the form of energy and chemicals (e.g., resins) that tend to have toxicological impacts. The fossil energy used in the production of adhesives is considered high compared to the other inputs [23]. Also, the volatile organic compounds (VOCs) in the adhesive formulations can pose environmental concerns. Therefore, it becomes imperative to understand the environmental impacts involved in the production, use, and different disposal options of LSL.

The objective of this study was to perform the LCA and quantify the cradle-to-grave (cradle-to-gate and gate-to-grave) environmental impacts of LSL. This study was the first to address gate-to-grave stages as part of a full cradle-to-grave environmental assessment of LSL. We also analyzed the three end-of-life (EoL) options of LSL, such as (i) landfilling (with methane capture) of LSL (base case), (ii) burning of LSL to capture heat, and (iii) recovering LSL for reuse. It is intended to be useful for future studies in the area of wood LCAs involving waste disposal and recycling strategies to optimize environmental trade-offs.

## **2. Methodology**

### **2.1 Goal and Scope Definition**

This LCA study followed the ISO 14040 and 14044 standards [24, 25], and Underwriters Laboratories Environment (ULE) product category rules (PCR) for North American Structural and Architectural Wood Products [26, 27]. The goal of the study was to quantify the cradle-to-grave environmental impacts of LSL in North America. The scope of this LCA study included all lifecycle stages of LSL, starting from resources management activities through end-of-life. Along with the environmental impacts, additional indicators such as energy use, waste generation, and many more [26, 27] indicators were also estimated in this study. The primary audience for the LCA study includes the LSL manufacturers, the American Wood Council, Canadian Wood Council, building developers and owners, architects, and other LCA practitioners.

### **2.2 Functional or Declared Unit**

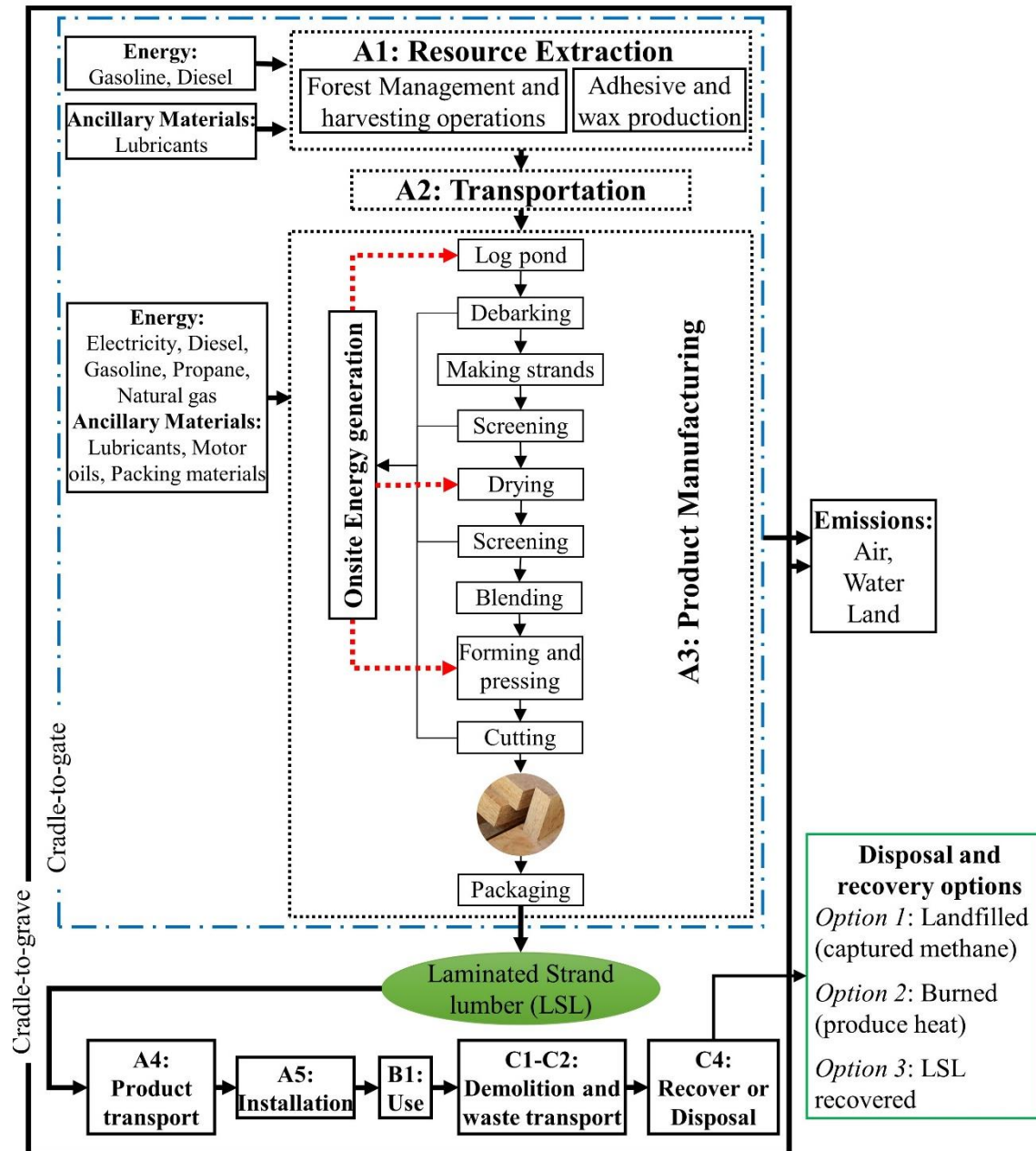
The role of the functional or declared unit in an LCA study is to give a reference against which all environmental inputs and outputs required to perform the functions of the LSL production system can be delineated. For the cradle-to-grave study, we used a functional unit of 1-m<sup>3</sup> of LSL used as the framing and disposed of at EoL.

### **2.3 Allocation**

Products and multiple co-products are common in wood-based manufacturing systems. Consequently, an LCA study needs to select an allocation method for assigning environmental impacts on each product. The wood products PCR requires using a mass allocation approach [27]. All inputs and direct emissions were allocated to various outputs (i.e., LSL and its co-products) based on their respective oven-dry (OD) mass.

### **2.4 System Boundary**

This study considered a cradle-to-grave (cradle-to-gate and gate-to-grave) system boundary (Figure 1). The cradle-to-gate system boundary of LSL begins with resource extraction and ends with LSL packaged to leave the mill gate (Figure 1). The key process included resource extraction (A1), transportation (A2), and product manufacturing (A3). Cradle-to-gate methylene diphenyl diisocyanate (MDI) resin production was part of A1. The gate-to-grave system consists of product transportation (A4), product installation (A5), product use (B1), building demolition (C1), and the EoL stage. Three disposal options considered for handling LSL after the building reached EoL were: i) landfill disposal with methane capture (baseline), ii) burning the LSL waste to produce heat and assessing its energy substitution benefits, iii) recovering LSL for reuse for a second functional life. The base case EoL considered the transport of (LSL) waste to a disposal site (C2) and disposal of waste (C4). The EoL options are discussed in detail in section 2.8.3. In this case, co-products produced during the LSL manufacturing process were partially burned onsite to generate heat for internal processes. The co-products were not tracked once they left the system boundary. This study included all materials and energy flows in the analysis. Hence, there were no cut-offs used in the impact assessment [20, 27].



**Figure 1** Cradle-to-grave system boundary for laminated strand lumber (LSL) system.

## 2.5 Description of LSL Life Cycle Processes

### 2.5.1 Resource Extraction (A1)

Whole hardwood logs were used to manufacture LSL in North America. The production of the logs began in the forest and included the forestry activities that are customary to central Canada [28] and the northeast-north central (NE-NC) region of the US [29]. Post-harvest and stand establishment activities such as site preparation and planting scenarios vary substantially with the owner of the timberland and region. The hardwood forest for these two regions did not include slash reduction activities and assumed natural forest regeneration [29]. The harvest included felling, skidding, processing, and loading for both commercial thinning and final harvest operations. The weighted average allocation to different processes considers inherent differences in site

productivity and energy usage by different kinds of logging equipment. Table 1 shows the contribution of the different regions supplying hardwood logs to produce LSL in North America. The weighted average density of incoming logs was 385 OD kg/m<sup>3</sup>, far less than the final product which has an expected range of 625 to 690 kg/m<sup>3</sup> depending on the grade of the LSL produced [12]. This difference is from the substantial pressing of the mat into the billet. This stage also included the production of secondary materials such as adhesive and wax used in LSL manufacturing.

**Table 1** Wood feedstock types and sources for laminated strand lumber (LSL) production, 1 m<sup>3</sup> (unallocated).

Feedstocks by regions	OD kg/ m <sup>3</sup> of LSL	% Contribution
Hardwood, logs, US Northeast	894.62	24.8
Hardwood, logs, Canada	977.21	75.2
TOTAL North American (weighted average) <sup>1</sup>	956.76	100

<sup>1</sup> The value of 956.79 oven-dry (OD) kg of hardwood log corresponds to 2.48 m<sup>3</sup>

### 2.5.2 Transportation (A2)

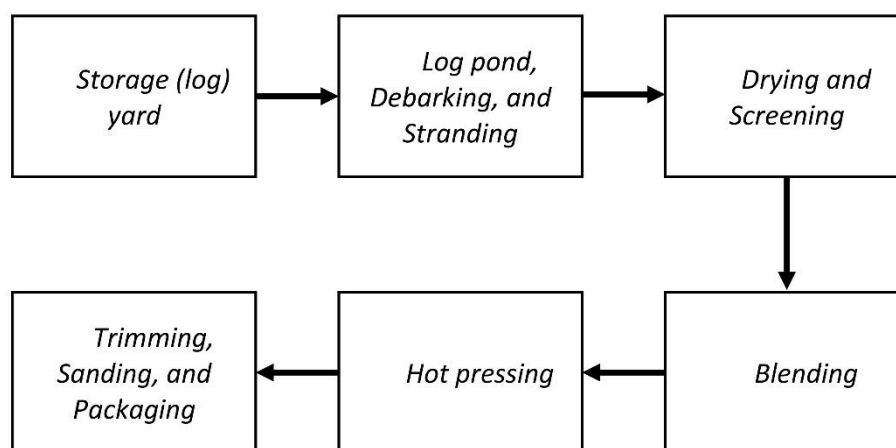
Forest resources, i.e., logs, were transported by trucks and rail from the forest to the mill. Resins and various ancillary materials and additives are used in LSL production. These materials were also transported in trucks and rail. Table 2 shows the weighted average haul distance for feedstocks and other materials used in LSL manufacturing. Most log transports were conducted by logging trucks, not rail, so its weighted distance was higher.

**Table 2** Weighted average delivery distance (one-way) for materials to the laminated strand lumber mills.

Input material	Mode of transport	Weighted transport distance (km)	Weighted coefficient of variation (%)
<i>Feedstocks</i>			
Hardwood, logs	Truck	204.16	51.4
	Rail	41.09	246.5
<i>Non-feedstocks materials</i>			
Resins and waxes	Rail	2170.19	50.6
Ancillary material	Truck	1015.94	73.2
	Rail	157.19	246.5
Other materials	Truck	824.20	27.7

### 2.5.3 LSL Manufacturing (A3)

The LSL manufacturing process is an automated, process-controlled, and linear process as illustrated in Figure 2. Once the logs reached the mill, they were debarked after softening in a heated log pond and then run through rotating knives of a stranding machine to produce strands. Strands were screened, dried, and then screened again for the bonding process. The waterproof adhesive, MDI, was sprayed on the strands (for strong bonding between strands) moving through a rotating drum. The strand mat was cured using steam and pressure, and then the LSL billets were cut to size and received a protective end [edge] seal before packaging and shipping. The weighted density of LSL was estimated at 647.2 OD kg/m<sup>3</sup> [including additives]. Although this density was much higher than the incoming logs, it is consistent with the values reported by other studies [12, 30, 31]. A brief description of the unit processes is presented next.



**Figure 2** Flow diagram of laminated strand lumber manufacturing processes (adapted from Craig and Abdullahi [12]).

**Storage Yard.** Freshly cut logs were received at the mill in tree length or shorter bolts varying from 2.5-2.6 meters (8.2-8.5 feet). In a “first-in, first-out” manner, logs were unloaded and stacked in the yard. The storage yard acts as a supply stock for the mill operations. Weight and moisture levels of all logs were determined. Log stackers or front-end loaders moved logs from the storage yard to the log pond. The inputs for storage yard operations were logs, electricity, fuel, and lubricants. Outputs were logs moved to log ponds.

**Log Pond, Debarking, and Stranding.** The logs were transported and placed in hot ponds where the wood temperature was raised to 20°C before debarking. Here, the logs were debarked using ring or drum debarkers. The bark was either used as a fuel within the mills or sold as a co-product. The debarked logs were stranded, reducing them to thin strands of 0.76-1.3 mm thick, 300-330 mm long, and 19-38 mm wide. Mills use disc screens to remove the unacceptable strands, either used as fuel in the mill or sold as co-products. The acceptable strands were sent to the green bins [32].

**Drying and Screening.** Strands stored in the green bins were fed to the rotary drum dryers to reduce their moisture content to less than 2-3% from a range of 50% to over 100% on a dry basis [33]. The emissions from the drying step include water vapors, small wood particles, and VOCs. The inlet temperature of the dryer can vary between 300-500°C. Hot air was passed through the strands until the desired moisture level was achieved, usually 20-25 minutes [32]. Dried strands were stored

in a dry storage bin where they were further screened to sort by size and then stored in separate bins [32].

**Blending.** In the blending step, the dried acceptable strands were blended with additives. The additives, adhesive and wax, were applied to the surface of strands in rotary drum blenders [32]. In addition, an emulsified wax was applied using spray nozzles. The adhesive used was MDI, which is on the US Environmental Agency (EPA) Toxics Release Inventory [34]. Zinc borate was also blended with the strands to prevent fungal decay and provide termite resistance. Based on the OD weight of LSL, adhesive and wax content usually ranges between 3-4% and less than 1%, respectively. The resultant mix from the blenders was sent to forming bins.

**Forming.** The blended furnish was fed onto conveyors into forming bins. These conveyors pass through the forming bin consistently to ensure uniform mass distribution. From the forming bins, the strands were fed onto “orienteers” to position all the strands in the long direction of the final product. After forming the mat, a release agent was sprayed on the mat surfaces to prevent it from clinging to the press platens [32].

**Hot Pressing.** A steam-injection press was used in LSL manufacturing. The purpose was to cure the additives [32]. The temperature in the press was maintained between 375°C and 410°C with a circulation of hot oil through a labyrinth made inside the platen. A separate labyrinth of channels built in the platens allows steam circulation. The cycle time for manufacturing LSL billet of thickness over 75 mm would be extremely high if hot pressing occurs without steam injection [32]. After the additives were fully cured, the LSL billets were removed from the press for cooling.

**Trimming, Sanding, and Packaging.** The cooled LSL billets were stacked for finishing, which depends on the requirements of customers. Finishing may require a simple trimming of the edges and ends, strapping, and shipping. Some LSL products require sanding (one or both sides), cutting to standard dimensions or sizes requested by the customer. Trimmings and dust from sanding were used as fuel but could be sold as a by-product. The discarded LSL billets were sold at a discounted price or simply used as fuel. The final LSL product was stacked and packaged for delivery to the customers. The LSL packaging materials included wooden spacers, plastic wrap, and cardboard (Table 3). Wooden spacers constituted the largest part of LSL packaging.

**Table 3** Materials used in packaging and shipping 1.0 m<sup>3</sup> LSL, North American average (unallocated).

Material	Value (kg)	Weighted coefficient of variation (%)
Plastic strapping	0.045	228.0
Plastic packaging (bags)	0.004	246.5
Plastic Packaging (wrap)	0.049	246.5
Wooden spacers	0.433	246.5
Cardboard spacers	0.114	81.1
Total	0.532	



## 2.6 Data Collection Method

For LSL, the life cycle inventory (LCI) data were obtained by surveying the two producers in North America for the year 2019. The survey used can be found as an appendix of Sahoo et al. [35]. Material and energy balances were calculated by a spreadsheet algorithm using data from primary and secondary data sources. From weight-averaging these material and energy values, environmental impacts were estimated by modeling emissions through SimaPro 9.1 software [36]. The primary data obtained from the surveys were weight-averaged using the formula shown in equation 1.

$$\bar{P}_w = \frac{\sum_{i=1}^N P_i x_i}{\sum_{i=1}^N x_i} \quad (1)$$

Where  $\bar{P}_w$  the weighted average of the values reported by the “N” mills,  $P_i$  was the reported “i” mill’s value such as production, and  $x_i$  is the fraction of the mill’s value to the combined total production of all the surveyed mills. Because the surveyed mill’s data varied between facilities, a statistical analysis was conducted. In this study, the weighted coefficient of variation was calculated [37]. The weighted coefficient of variation ( $CoV_w$ ) is the weighted standard deviation ( $sd_w$ ) divided by the weighted mean  $\bar{P}_w$  as shown in equation 2.

$$CoV_w = \frac{\sqrt{(\sum_{i=1}^N w_i \times (x_i - \bar{x}_w)^2) / [(N' - 1) \sum_{i=1}^N w_i] / N'}}{\bar{P}_w} \quad (2)$$

Where,  $w_i$  is the weight of the  $i$ th observation,  $N'$  is the number of nonzero weights, and  $\bar{x}_w$  is the weighted mean of the observations ( $N$ ). Whenever missing data occurred for survey items, they were checked with facility personnel to determine whether it was an unknown value or zero. Missing data were carefully noted, so they were not averaged as zeros. Any outliers were resolved by contacting mill personnel. The data from the surveys were assimilated and converted to a unit production basis of volume in the SI unit of  $m^3$  that represents a composite of the North American mills surveyed but may not represent any specific mill. The secondary data on transport, electrical grid inputs, fuels, and forest resource activities were obtained from DATASmart [38] which represents the North America region data, and Ecoinvent 3.6 (Ecoinvent, Zurich, Switzerland). The previous LCA study on LSL production [32] and other sources [39] were used to supplement the emissions data which were not provided by the mills. The secondary data on forest management and harvesting used in this study was modified from earlier studies to reflect species management [29]. Primary data were not collected for inputs, including forest resources and adhesive and wax production.

## 2.7 Gate-to-Gate Lifecycle Inventory

Table 4 represents LSL production’s gate-to-gate inputs (materials, transport, fuels, and energy) and outputs (main products, co-products, emissions, and waste). These data were linked to the upstream unit processes for forest resources, ancillary materials, transportation, fuels, and electricity to calculate cradle-to-gate environmental impacts for LSL.

**Table 4** Environmental inputs and outputs to produce 1 m<sup>3</sup> of laminated strand lumber, North American (unallocated, gate-to-gate, weight-averaged).

Description	Value	Outputs	Value
<b>Products, co-products (OD kg)</b>		<b>Emissions to air (kg)</b>	
Laminated Strand Lumber	647.21 (65.33%)	Acetaldehyde <sup>a</sup>	3.10E-03
Strands	32.59 (3.29%)	Acrolein <sup>a</sup>	7.07E-04
Log yard/pond debris	22.49 (2.27%)	Benzene <sup>b</sup>	4.47E-05
Hog fuel	43.92 (4.43%)	Carbon monoxide <sup>a</sup>	6.90E-02
Bark	210.7 (21.27%)	Carbon dioxide, biogenic <sup>b</sup>	4.66E+02
Short stands	7.43 (0.75%)	Dust (wood) <sup>b</sup>	1.49E-01
Wood residues	9.46 (0.95%)	Formaldehyde <sup>a</sup>	2.72E-03
Other wood residues	16.92 (1.71%)	Hydrogen chloride <sup>b</sup>	3.10E-04
<b>Resource inputs</b>		Lead <sup>a</sup>	8.15E-06
Roundwood logs	2.48 m <sup>3</sup>	Mercury <sup>a</sup>	1.21E-06
Wax	0.61 kg	Methane <sup>b</sup>	3.00E-04
Adhesive -MDI	30.82 kg	Methane, Biogenic <sup>b</sup>	5.90E-03
Zinc Borate	0.26 kg	Methanol <sup>b</sup>	2.10E-03
Emulsified wax	2.27 kg	Methylene diisocyanate <sup>b</sup>	4.30E-03
Water, municipal	205.43 L	Nitrous oxide (NO <sub>x</sub> ) <sup>b</sup>	2.91E-01
<b>Fuel and energy inputs</b>		Dinitrogen monoxide (N <sub>2</sub> O) <sup>b</sup>	7.09E-02
Electricity, at grid	276.01 kWh	PM <sub>2.5</sub>	3.68E-02
Wood fuel	264.56 OD kg	Particulates, PM10-PM2.5 <sup>a</sup>	9.23E-02
Propane	9.78 L	PM10 <sup>a</sup>	1.65E-01
Natural gas	0.4 m <sup>3</sup>	Particulates, unspecified <sup>a</sup>	2.74E-02
Diesel	2.48 L	Phenol <sup>b</sup>	3.30E-03
Gasoline	0.01 L	Propanal <sup>b</sup>	2.70E-03
<b>Ancillary materials inputs</b>		Sulfur dioxide <sup>a</sup>	3.95E-02
Sealant	0.38 kg	VOC <sup>a</sup>	3.65E-01
Release agent	1.04 kg	<b>Wastes to treatment (kg)</b>	
Motor oil	0.02 kg	Wood waste	0.239
Greases	0.01 kg	Boiler ash	7.995
Hydraulic fluid	0.19 kg	Recycled metals	0.471
Antifreeze	0.13 L	Plastic strapping	0.006
Lubricating fluid	0.07 kg	Cardboard	0.023
<b>Transportation</b>		Paper	0.002
Wood feedstock	638.97 tkm	Batteries	0.0001
Resins and wax	133.75 tkm		
Ancillary material	11.19 tkm		

<sup>a</sup>Emissions data are from survey data; <sup>b</sup>Emissions data are estimated from US Environmental Protection Agency's air emissions factors for engineered wood products manufacturing [39], or previous study [32], or literature [40]

The values in parenthesis of the inputs in Table 4 indicate their percent allocation applied in the LCA. According to the weighted average approach, 1 m<sup>3</sup> LSL (647.21 OD kg) production required 2.48 m<sup>3</sup> (956.76 OD kg) wood feedstock. Most of the energy required in LSL manufacturing came from mill residues (bark, hogged fuel) used in boilers augmented slightly by natural gas. Wood fuel use (264.56 OD kg/m<sup>3</sup>) was mainly comprised of bark. Electricity consumed onsite was calculated to be 276 kWh/m<sup>3</sup>, unallocated. Natural gas and propane were the primary fossil fuels used on site. Table 5 shows the onsite energy inputs for the mills in LSL manufacturing.

**Table 5** Onsite energy inputs per m<sup>3</sup> laminated strand lumber, North American average (unallocated).

Inputs	Quantity	Weighted coefficient of variation (%)	Energy (MJ)
Electricity	276.01 kWh	1.27	-
Wood fuel <sup>a</sup>	264.56 OD kg	30.10	5529
Propane <sup>b</sup>	9.78 L	244.19	227
Natural gas <sup>c</sup>	0.40 m <sup>3</sup>	81.13	15
Diesel <sup>d</sup>	2.48 L	1.08	89
Gasoline <sup>e</sup>	0.01 L	246.50	<1

Heating values of the inputs (MJ/unit): <sup>a</sup>20.9, <sup>b</sup>23.2, <sup>c</sup>36.6, <sup>d</sup>36.0, <sup>e</sup>32.0

A smaller  $CoV_w$  for electricity indicated the less spread around the mean, indicating a good data quality. Electricity from the grid was used to operate equipment within the plant, including conveyors, refiners, fan motors, hydraulic press motors, sanders, pumps, and emission control systems. The electricity use considered the weighted average of regional variations (75:25) during the development of the LCI: 75% from the electricity grid in Ontario, Canada (CO<sub>2</sub> emission factor 0.095 kg/kWh) and 25% from NPCC, US grid (CO<sub>2</sub> emission factor 0.251 kg/kWh) [38]. Wood fuel at 5,529 MJ/m<sup>3</sup> LSL was the primary heating source used in the LSL process, including heat for drying strands, steam or oil for log ponds, and hot pressing. In addition, fuels such as diesel, propane, and gasoline were used for handling material onsite. Onsite air emissions were derived from the surveyed mills along with pertinent emissions data categorized by the USEPA. When available, surveyed air emission data as primary data were selected rather than secondary data.

## 2.8 Gate-to-Grave Model for LSL Products

The assessment of cradle-to-grave life cycle impacts of engineered wood products is essential for understanding the environmental trade-offs as opposed to their counterparts. Therefore, a gate-to-grave model was constructed and evaluated. The gate-to-grave stages of an average LSL product life cycle and the assumptions made are briefly described in this section.

### 2.8.1 LSL Product Transport (A4)

LSL was transported to warehouses for distribution and then to installation sites. The LSL industry experts were contacted to confirm the data assumption on distance and mode of transportation [41]. This study assumed 80% and 20% of LSL was transported by rail and truck (i.e., diesel flatbed trailer), respectively. The distance between mills and warehouses was considered to be 1,000 km. This value was based on the estimation of the location of production facilities to major consumer locations (i.e., major cities). The transportation distance between the warehouse and installation site was assumed to be 100 km [41]. These transportation values were a source of uncertainty and were assessed later for their sensitivity to the overall environmental impacts.

### 2.8.2 Installation and Use of LSL (B1)

LSL is mostly used in headers and beams, wall stud applications, roof beams and rafters, truss chords, rim boards, and stair stringers, etc. This phase included material and energy inputs in installing, using, and maintaining the LSL products. A 3% loss in mass was assumed to account for the trimming and finishing process in consultation with the industry experts [41]. Further, it was assumed that no preservatives are used in LSL products owing to their intrinsic durability and no exterior exposure. A service life of 80 years was considered in the study with no added repair or maintenance inputs in the use phase until its removal at the end of the use phase.

### 2.8.3 Disposal of LSL (C1-C4)

Three disposal options were evaluated in this study. The options are listed below and described subsequently.

**Option 1 (baseline):** Buildings were demolished at 80 years and LSL, as waste was disposed of in a local landfill that captured methane.

**Option 2:** Buildings were demolished at 80 years and LSL; a waste was burned to generate heat to displace an equivalent amount of natural gas

**Option 3:** Buildings were deconstructed with the recovery of LSL. The recovered LSL was used for a second lifetime, assuming no decline in wood quality.

Landfill disposal was considered a common practice because of cost while indirectly offering an environmental advantage for carbon storage. The disposal phase of LSL consisted of the demolition (C1), transport to landfill-site (C2), processing of LSL waste (C3), and final disposal in the landfill. The contribution of the demolition phase (C1) to the environmental impacts of the whole LSL life cycle was considered negligible in this case [42-44]. Waste generated from the demolition was transported to a landfill site. The distance to the landfill location was taken as 40 km, and a diesel dump truck was used to transport waste LSL from the demolition site. There was no further processing of LSL waste at the landfill and hence no contribution to environmental impacts. About 12% of wood decomposes anaerobically into gas when placed in the landfill [45], and wood content in LSL products was taken as 97% with 50% carbon by weight. Around 1,010 kg CO<sub>2</sub> eq long-term carbon storage was estimated for the cradle-to-grave life cycle of 1 m<sup>3</sup> of LSL (Table 6).

**Table 6** Carbon storage per m<sup>3</sup> of LSL (cradle-to-grave).

Parameter	Value (%)
Carbon breakdown in landfill	12%
Carbon storage in landfill	88%
Wood in LSL	97%
Carbon content in LSL	50%
Net long-term carbon storage (kg CO <sub>2</sub> eq)	1,010

Using methane capture technology, Table 7 shows the emissions of biogenic methane and carbon dioxide, primary components of landfill gas estimated using the WARM model from anaerobic storage of wood waste [45].

**Table 7** GHG emissions from wood landfilled with standard methane capture.

GHG Emissions	Kg/OD kg wood	Kg/m <sup>3</sup> of LSL
Methane, biogenic <sup>1</sup>	0.0090	5.8249
Carbon dioxide, biogenic <sup>1</sup>	0.0303	19.5781
Carbon dioxide, biogenic <sup>2</sup>	0.1155	74.7528
Carbon dioxide, biogenic <sup>3</sup>	0.0495	32.0369

<sup>1</sup>Released directly into the air. <sup>2</sup>Released after energy recovery (70%). <sup>3</sup>Release after flaring (30%) - energy not recovered.

In the second disposal option, the generated heat from the burning LSL was assumed to displace an equivalent amount of natural gas. The higher heating value (HHV) of LSL wood was considered as 20.9 MJ/kg and a heating efficiency was taken as 70%. The useful heat generated from burning LSL was 9,470 MJ. For natural gas, the assumed HHV was 38.3 MJ/m<sup>3</sup>, with a heating efficiency was 85%. Based on this, 1 m<sup>3</sup> of LSL can displace 291 m<sup>3</sup> of natural gas.

The third disposal option assumed recovery of LSL from building deconstruction for reuse and thus considered resource efficient. Deconstruction is not common in North America due to the high cost of the deconstruction process and the lack of a robust market for the reuse of deconstructed wood [46]. However, recycling wood products would play an important role in the sustainable management of forest resources, given their increasing global demand [47, 48]. The LCI parameters are considered (Table 8) for the modeling of recycling and reuse of the LSL for a second functional life where it will displace the virgin LSL. The assumptions were taken in consultation with the wood industry experts [41] and were also supported by Bergman et al. [47] and Roussat et al [48]. The analysis considered no decline in wood quality and carbon stored in the wood when reused but with a 17% mass loss [47]. The waste generated after the second functional life from demolishing was considered through the landfill route.

**Table 8** Inputs for 1 m<sup>3</sup> laminated strand lumber (LSL) recovered and reused [47].

Inputs parameter	Value	Unit
<b>1. Removal (deconstruction)</b>		

Losses in recovery	17	%
LSL removed	684.15	OD kg
Disposal: Landfilled with methane capture	110.03	OD kg
Transport, Single unit truck, gasoline-powered/US	0.62	tkm
Transport, Single unit truck, diesel-powered/US	0.51	tkm
Gasoline, combusted in equipment/US	1.53	liter
Electricity, at grid, US/US	14.3	kWh
<b>2. Storage</b>		
Transport, Single unit truck, gasoline-powered/US	17.10	tkm
Transport, Single unit truck, diesel-powered/US	17.10	tkm
Electricity, at grid, US/US	2.86	kWh
Residual fuel oil, combusted in industrial boiler/US	0.22	liter
Natural gas, combusted in industrial boiler/US	0.00009	m <sup>3</sup>
Gasoline, combusted in equipment/US	1.44	liter
<b>3. Product Transport</b>		
Transport, Single unit truck, diesel-powered/US	32.84	tkm

## 2.9 Data Quality

This study collected data (cradle-to-gate) from LSL manufacturers in North America that used average technology. Primary data for the LCI collected through surveys followed the ISO 14040 standard. The production facilities surveyed were selected to be representative (100% of the total LSL industry) of North American production practices. A mass balance was performed for the two plants for data quality assurance. The mass allocations approach was used to assign environmental impacts to the product (e.g., LSL) and co-products (e.g., mill residues sold to outside customers). The inventory data for gate-to-grave stages were collected based on consultations with industry experts and was supported by other studies on wood products [47, 48]. It was assumed to represent the average scenario of LSL transport from mill, installation and use, and disposal at the end of life.

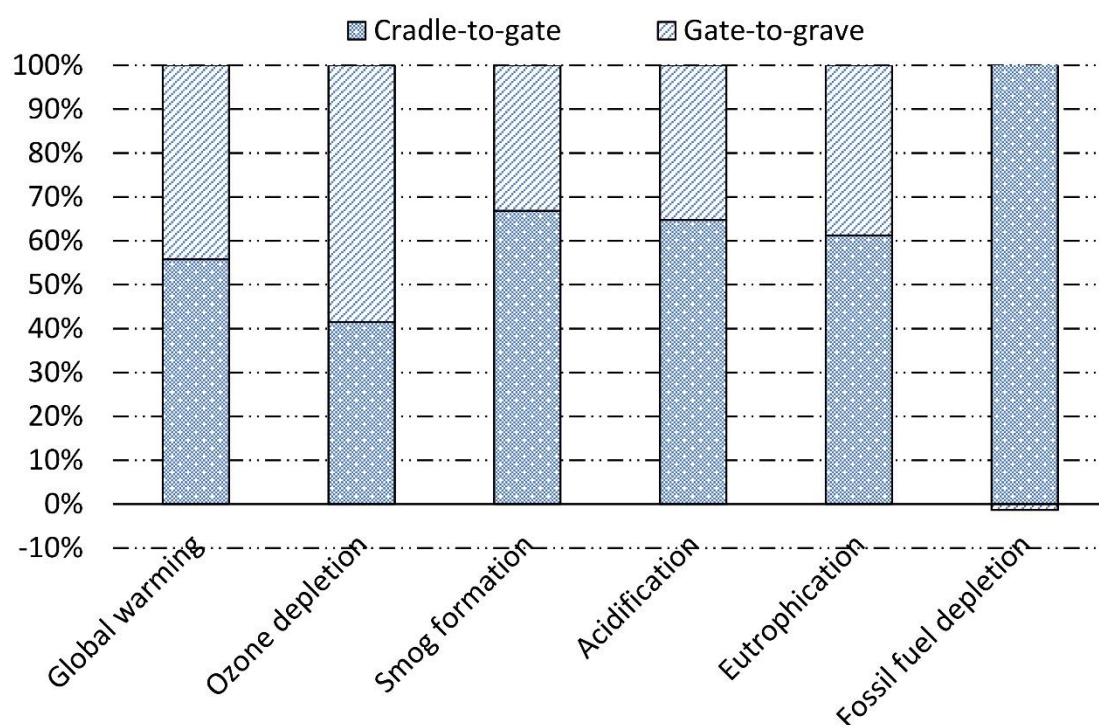
## 2.10 Life Cycle Impact Assessment (LCIA) Method

The LCIA phase establishes links between the LCI results and potential environmental impacts. The magnitude and significance of the potential environmental impacts as a set of indicators are evaluated using the TRACI [49], CML [50], and CED [51] methods available in the SimaPro software (version 9.1). Each impact indicator is a measure of an aspect of a potential impact. The LCIA phase in this study included only the mandatory steps: classification and characterization. The normalization and weighting steps were not in the scope of the study. The study does not make value judgments about the impact indicators, meaning comparison indicator values are not valid. Additionally, each impact indicator value is stated in units that are not comparable to others. For the same reasons, indicators should not be combined or added. The LCIA results were intended to be used for the identification of hotspots in the LSL systems (cradle-to-gate and cradle-to-grave) studied. The required indicators recommended by the PCR and ISO 21930 were also included in the assessment. The primary fuels were categorized into non-renewable (fossil and nuclear) and renewable (biomass, geothermal, solar, wind, hydro).

### 3. Results and Discussions

#### 3.1 LCIA Results

Figure 3 shows the relative contribution of cradle-to-gate and gate-to-grave lifecycle stages towards the total environmental impacts of LSL. The gate-to-grave lifecycle stages made a significant contribution (e.g., ~44% to LSL's total GW impact) to overall LCA results, which provide the importance of including the whole life cycle in the LCA of wood products. The fossil fuel depletion impacts showed substitution benefits of landfill gas capture and energy recovery (disposal option 1).



**Figure 3** Percent share of cradle-to-gate and gate-to-grave lifecycle stages in the overall environmental impacts of LSL.

The overall LCA results (with absolute values of the impact indicators and percentage contribution of the individual lifecycle stages) were presented in Table 9. Certain impact indicators such as water use, solid waste were only based on LCI indicator results.

**Table 9** Summary of life cycle environmental impacts per m<sup>3</sup> of laminated strand lumber produced in North America (mass allocation).

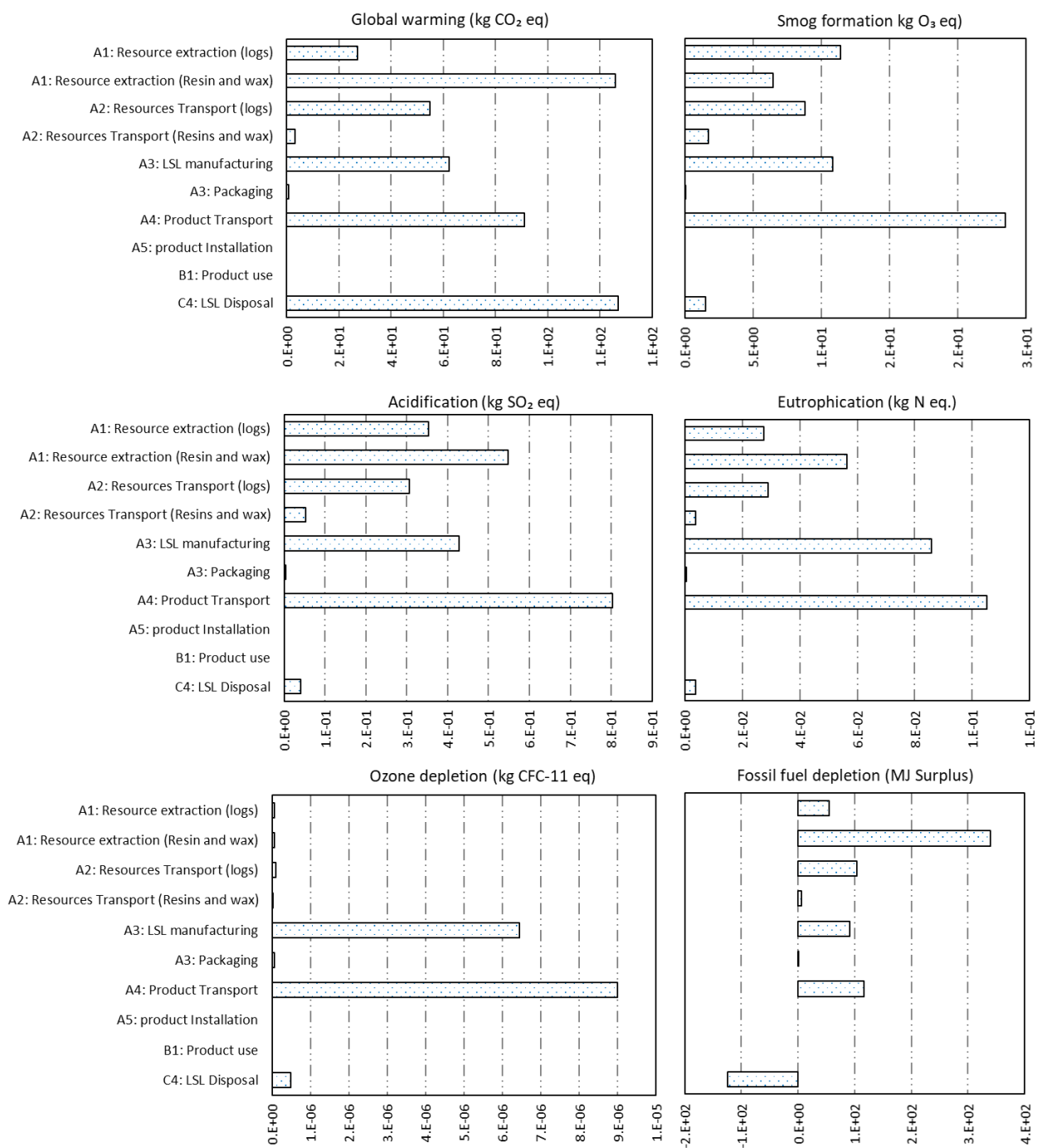
Impact category	LCIA Method	Cradle-to-grave (A1-C4)	Cradle- to-gate (A1-A3)	A1 (%)	A2 (%)	A3 (%)	Gate-to- grave (A4-C4)	A4 (%)	B1 (%)	C1-C4 (%)
<b>Core mandatory impact indicators</b>										
Global warming (kg CO <sub>2</sub> eq)	TRACI 2.1	492.92	274.9	55.70	21.45	22.85	218.02	42	0	58
Ozone layer depletion (kg CFC-11 eq)	TRACI 2.1	1.62E-05	6.72E-06	1.82	1.54	96.64	9.00E-06	95	0	5
Acidification (kg SO <sub>2</sub> eq)	TRACI 2.1	2.54	1.7	53.07	21.43	25.50	0.84	95	0	5
Eutrophication (kg N eq)	TRACI 2.1	0.31	0.2	41.26	16.37	42.37	0.11	97	0	3
Smog formation (kg O <sub>3</sub> eq)	TRACI 2.1	64.50	39.51	45.37	27.04	27.59	24.99	94	0	6
Abiotic depletion (MJ, NCV)	CML baseline	4114.15	4,015.88	66.43	18.37	15.20	98.27	849	0	-749
Fossil fuel depletion (MJ Surplus)	TRACI 2.1	590.14	597.92	65.97	18.53	15.50	-7.78	-1502	0	1602
<b>Use of primary resources</b>										
Renewable primary energy carrier used as energy (MJ, NCV)	CED	5201.13	5,190.65	0.49	0.03	99.48	10.48	95	0	5
Renewable primary energy carrier used as material (MJ, NCV)	CED	13063.02	13,063.02	100	0	0	0.00	0	0	0
Non-renewable primary energy carrier used as energy (MJ, NCV)	CED	6649.93	6,512.45	45	11	43	137.48	633	0	-533
Non-renewable primary energy carrier used as material (MJ, NCV)	CED	1100.11	1100.11	0	0	100	0	0	0	0
Total (MJ, NCV)	CED	26014.19	25866.23				147.96			
<b>Mandatory inventory parameters</b>										
Consumption of freshwater resources (m <sup>3</sup> )	LCI indicator	8.18	5.4	48.70	0.19	51.11	2.8	0	0	100
<b>Indicators describing waste</b>										



Hazardous waste disposed (kg)	LCI indicator	0.63	6.02E-01	92.03	0.01	7.84	3.11E-02	0	0	100
Non-hazardous waste disposed (kg)	LCI indicator	31.55	2.96E+01	1.87	0.00	97.97	1.95E+00	96	0	4
High-level radioactive waste, conditioned, to final repository (m <sup>3</sup> )	LCI indicator	1.57E-05	1.57E-05	0.00	0.00	100.00	0.00E+00	0	0	0
Intermediate- and low-level radioactive waste conditioned, to final repository (m <sup>3</sup> )	LCI indicator	2.36E-05	2.34E-05	0.21	0.24	99.57	1.70E-07	0.00	0	100

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The most relevant lifecycle stages in their decreasing contribution to their cradle-to-grave GW impacts were resource extraction (A1), end-of-life (EoL), transportation [resources (A2) and product (A4)], and LSL manufacturing(A3). Further, the breakdown of characterization results by life cycle stages is shown in Figure 4, where the most significant unit processes (hotspots) were identified for different impact categories as well as for different life cycle stages.



**Figure 4** Characterization impacts of different life cycle stages with disposal option 1.

### 3.1.1 Global Warming (GW)

The cradle-to-grave GW impact was 493 kg CO<sub>2</sub> eq for 1 m<sup>3</sup> LSL. Around 56% and 44% of total GW impacts of LSL were contributed by cradle-to-gate and gate-to-grave life cycle stages (Table 9). In the cradle-to-gate GW impacts (around 275 kg CO<sub>2</sub> eq/m<sup>3</sup>), the major contribution was from the resource extraction stage [A1] (55.7%), especially from the resin and wax (126 kg CO<sub>2</sub> eq) and forest resources (27 kg CO<sub>2</sub> eq) (Figure 4). The use of resin and wax in the manufacturing stage was identified as a hotspot, noting the need for environment-friendly alternatives for this role. Transport activities [A2] caused 22% of the GW impacts in cradle-to-gate LCA results. The transportation [A4] had a much greater contribution (42%) in gate-to-grave GW impacts. Longer transport distances between the mill and LSL installation site (1000 km from LSL mill to warehouse + 100 km from warehouse to installation site) increased their share in the gate-to-grave GW impacts. Here, the increasing demand for the use of engineered woods like LSL in the residential sector had drawn attention to sustainable logistics and supply chain management which needs to be studied in the future.

Another major hotspot was the landfill disposal (127 kg CO<sub>2</sub> eq), contributing 58% to the gate-to-grave model and 23% to the total GWP. The anaerobic decomposition of LSL results in the release of landfill gases. It was estimated (Table 7) that 5.82 kg CH<sub>4</sub>/m<sup>3</sup> of LSL (25% of total CH<sub>4</sub> generated in the landfills) to be released into the atmosphere from the landfill disposal option and thus contributed to high GW impact. However, it was realized that the magnitude of these impacts could change if the recycling of LSL waste or any other disposal method like incineration was considered. Recycling LSL could increase the life of carbon stored in the LSL product. However, only one functional life was considered in this study. A comparative evaluation of variation in disposal mechanisms is presented later in the paper.

### 3.1.2 Smog Formation (SF)

The smog formation (SF) impacts were associated with the formation of photochemical oxidants. The cradle-to-gate and gate-to-grave stages shared 67% and 33% of the total SF impacts of the LSL (64.50 kg O<sub>3</sub> eq/m<sup>3</sup>), respectively. In this study, the SF impacts were mainly caused by emissions of NO<sub>x</sub>, hydrocarbons in transportation activities, and VOCs released from the solvents in the used resin and wax (Figure 4). All these life cycle stages (A1-A4) contributed 98% to the total SF impacts. The resource extraction for both logs and the resin and wax [A1] and their transportation [A2] were identified as major hotspots in SF impacts of cradle-to-gate stages. The LSL manufacturing was caused nearly 28% of the SF impacts. The influence of change in the adhesive used in LSL manufacturing and feedstock transportation distances was further studied in the sensitivity analysis (Section 3.4). The product transportation [A2] had the largest SF impact (94%) in the gate-to-grave life cycle stage of LSL, which came from fuel use in the transportation process.

### 3.1.3 Acidification (AC)

The overall acidification (AC) impact of the studied LSL system was 2.54 kg SO<sub>2</sub> eq/m<sup>3</sup>. The cradle-to-gate and gate-to-grave stages contributed 65% and 35% of the total AC impacts, respectively. The AC impacts were mainly caused by emissions of nitrogen oxides (NO<sub>x</sub>) and sulfur dioxide (SO<sub>2</sub>). The SO<sub>2</sub> emissions were primarily from the combustion of fossil fuels for energy requirements at

the mill and fuel burned in the transportation processes. The source of these acidifying emissions was resource extraction (36%), product transportation (32%), and resource transportation (14%) stages, together accounting for 81% of the total AC impacts. In the LSL manufacturing facility, the NO<sub>x</sub> emissions were mainly caused by the provision of energy for LSL production.

#### 3.1.4 Eutrophication (EU)

The cradle-to-grave eutrophication (EU) impacts of LSL was 0.31 kg N eq/m<sup>3</sup> (61% from cradle-to-gate and 39% from gate-to-grave). Within the cradle-to-gate results, the LSL manufacturing and resource extraction processes were the major contributors to EU impacts (Figure 4). The emissions from the provision of required energy and adhesives in the LSL manufacturing [A3] caused 42% of the cradle-to-gate EU impacts. The NO<sub>x</sub> emissions, the main source of EU impacts, were released during the harvesting of wood feedstock and production of adhesives. The product transportation [A2] stage contributed 97% of gate-to-grave EU impacts which were mostly derived from the combustion of fuels.

#### 3.1.5 Ozone Depletion (OZD)

Referring to the ozone depletion (OZD) impacts of the analyzed LSL system, the share of cradle-to-gate and gate-to-grave impacts was 41% and 59%, respectively. Among all life stages, transportation of LSL product (A4) and LSL manufacturing (A3) were the major hotspots contributing 56% and 40% of cradle-to-grave OZD impacts, respectively. In the cradle-to-gate LCA results, the LSL manufacturing stage [A3] caused most (96%) of the OZD impacts. The sources of OZD emissions were the use of antifreeze coolants, adhesives, and wax. Releases of chemicals influencing ozone depletion were reported in a very small quantity in terms of absolute values, but they have a high OZD. Use of such inputs cannot be avoided in the manufacturing of wood products, however, the alternative with lower OZD needs to be investigated in detail. In gate-to-grave, it was the LSL transportation stage [A4] that contributed nearly 95% of the OZD impacts.

#### 3.1.6 Fossil Fuel Depletion (FFD)

Figure 4 shows the breakdown of FFD contribution by each life cycle stage. The Fossil fuel depletion (FFD) impact of the analyzed LSL system was 590 MJ/m<sup>3</sup>. The major contribution was observed in the resource extraction stage. In the cradle-to-gate, the resource extraction stage accounted for 66% of the impacts. The FFD in the resource extraction processes for resins and wax (339 MJ) was much greater than the harvesting activities in forest resources (60 MJ). FFD impact of the LSL manufacturing stage (~6 MJ) was relatively small due to the use of mill residues for energy production, which subsequently reduced the use of fossil fuels. The FFD impact from the transportation product [A4] was 118 MJ and mostly came from the use of fossil fuel in transport equipment. A negative FFD was noticed in the gate-to-grave stage due to methane recovery in the landfill. The generated landfill gas was considered captured in the disposal of LSL products that offset fossil fuel use to an extent (-125 MJ).

### 3.2 Comparison of LSL Waste Disposal Options

Table 10 presents the environmental impacts of individual EoL or disposal options [as well as the whole life cycle (cradle-to-grave) of LSL] considering the substitution benefits (i.e., natural gas displaced by fuels/energy generated in the disposal of LSL and virgin-LSL products by recovery LSL at the 1<sup>st</sup> EoL of LSL). The absolute values of GW and FFD impacts were negative for option 2 due to a large amount of natural gas being substituted by energy generated from the burning of LSL at the EoL. For option 3, all impact categories values were negatives except FFD as LSL was recovered and reused and negligible energy was recovered. Considering the whole life cycle (cradle-to-grave), the burning of LSL waste (option 2) resulted in negative GW impacts owing to the largest substitution benefits of generated heat that replaces natural gas.

**Table 10** Environmental impacts of LSL waste disposal options.

Impact category	Impacts of disposal options (C4)			Cradle-to-grave impacts with each disposal option (A1-C4)		
	Landfill disposal (Option 1)	LSL waste burning (Option 2)	LSL recovery for reuse (Option 3)	Option 1	Option 2	Option 3 <sup>†</sup>
GW (kg CO <sub>2</sub> eq)	1.27E+02	-7.12E+02	-1.59E+02	4.93E+02	-3.47E+02	2.07E+02
OZD (kg CFC-11eq)	4.86E-07	9.55E-05	-7.42E-06	1.62E-05	1.11E-04	8.30E-06
SF (kg O <sub>3</sub> eq)	1.51E+00	3.60E+00	-1.74E+01	6.45E+01	6.66E+01	4.56E+01
AC (kg SO <sub>2</sub> eq)	4.11E-02	4.29E-02	-5.51E-01	2.54E+00	2.55E+00	1.95E+00
EU (kg N eq)	3.77E-03	4.58E-01	-4.91E-02	3.09E-01	7.63E-01	2.56E-01
FFD (MJ Surplus)	-1.25E+02	-1.69E+03	3.84E+01	5.90E+02	-9.80E+02	7.53E+02
Net carbon storage (kg CO <sub>2</sub> eq) <sup>‡</sup>				1.01E+03	-	1.32E+03

<sup>†</sup>Includes landfill disposal after the end of second useful life

<sup>‡</sup>Carbon stored in the product and landfill

The landfill disposal has the highest GW impacts caused by the GHGs released (i.e., CH<sub>4</sub>) due to the anaerobic decomposition of LSL waste. Option 3 has GW impacts coming from the operations in the recovery of LSL and product transportation to and from storage. Considering carbon storage, options 1 (stored 1,010 kg CO<sub>2</sub> eq in landfill) and 2 (stored 1,320 kg CO<sub>2</sub> eq in product and landfill) are better than option 2. In option 2, atmospheric carbon stored in the wood was released into the atmosphere during the burning process. In OZD impacts, the burning scenario was performing worse than the other two because of the emission of ozone-depleting substances in the burning of LSL waste laden with adhesives. It was similar order for SF impacts with higher impacts from burning of LSL followed by recovery and reuse. The emissions of VOCs, NO<sub>x</sub>, and hydrocarbons cause higher SF impacts. In the AC category, most of the contribution was from emissions of NO<sub>x</sub> and SO<sub>2</sub> coming mainly from the transportation activities which were almost similar for option 1 and option 2.

### 3.3 Biogenic Carbon Uptake and Release

Wood is a biobased product and contains biogenic carbon. ISO 21930 provides set rules for accounting for biogenic carbon flows. The biogenic carbon flows (kg CO<sub>2</sub> eq.) to and from the environment were listed in inventory Table 11.

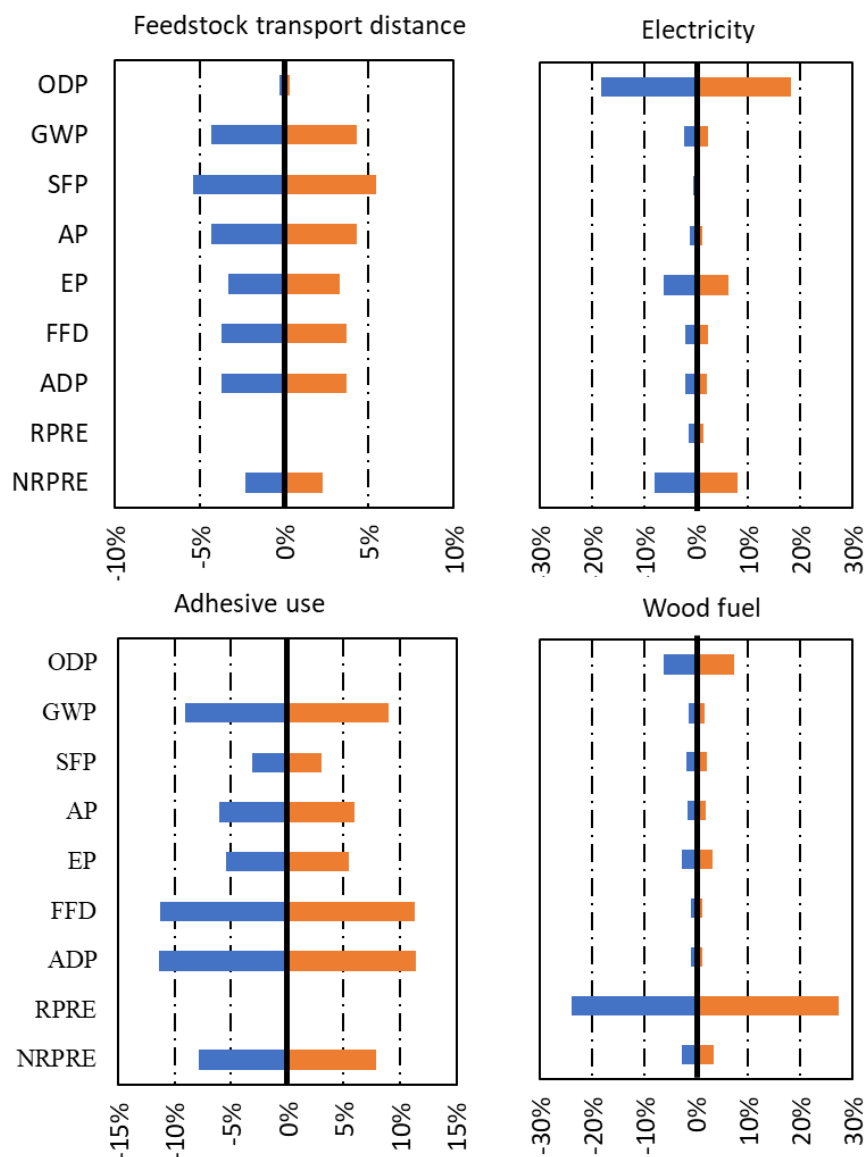
**Table 11** LCI flows related to biogenic carbon uptake and release.

Details of biogenic carbon flows (kg CO <sub>2</sub> eq)	Total	A1	A2	A3 (manufacturing)	A3 (packaging)	C4
Biogenic Carbon Removal from Product	-1754.05	-1754.05	-	-	-	-
Biogenic Carbon Emission from Products (including residues)	1269.02	-	-	123.14	-	1145.88
Biogenic Carbon Removal from Packaging	-1.00	-	-	-1.00	-	-
Biogenic Carbon Emission from Packaging	0.16	-	-	-	0.16	-
Biogenic Carbon Emission from biomass boiler (Internal heat)	485.03	-	-	485.03	-	-

One kg of OD wood containing 0.5 kg carbon (assuming 50% carbon content) is equivalent to 1.83 kg CO<sub>2</sub> eq. The CO<sub>2</sub> uptake by the forests was considered as negative emission (-1). The release of the CO<sub>2</sub> as the main product (LSL), co-products, and combustion emissions in the manufacturing mill (A3) were treated as positive emissions (+1). This -1/+1 approach helped in accounting for all biogenic carbon flows. The remaining GHG gases were characterized according to their global warming potentials. According to the ISO 21930, the biogenic carbon flow in LSL manufacturing and LSL packaging were reported separately (Table 11). The production of 647.21 kg LSL (1m<sup>3</sup>) resulted in biogenic carbon removal equal to -1754.05 kg CO<sub>2</sub> eq. About +1145.88 kg CO<sub>2</sub> eq carbon was in the LSL product. Overall, 1269.02 kg CO<sub>2</sub> eq. (including 123.14 kg CO<sub>2</sub> eq. as co-products) biogenic carbon was emitted in the A3 stage as the main product and co-product.

### 3.4 Sensitivity Analysis

Figure 5 shows the variations in the environmental impacts of LSL due to changes in the major input parameters in the LCA study. A 20% change in feedstock transport distance impacted the SF impact indicator most (5%) followed by a 4% change in GW, AC, and AD indicators. EU and NRPRE showed a 2% change in absolute values.



**Figure 5** Influence of 20% change in input parameters on cradle-to-grave LCA results per m<sup>3</sup> LSL. (OZD: ozone depletion, GW: global warming, SF: smog formation, AC: acidification, EU: eutrophication, FFD: fossil fuel depletion, AD: abiotic depletion, RPRE: renewable primary resources as energy, NRPRE: non-renewable primary resources as energy).

Given that transportation was the main contributor to these impact indicators, an improvement opportunity can be identified from the sensitivity analysis. The change in electricity inputs showed significant changes in OZD, NRPRE, and EU indicators, 18%, 8%, and 6%, respectively. The amount of adhesive used in the LSL impacted mostly GW, ADP, and NRPRE. A 20% increase or decrease in the quantity of adhesive used in LSL influenced all impact categories, especially an 8-11% increase or decrease in the values of AD, FFD, GW, and NRPRE. The only impact category RPRE was sensitive to the amount of wood fuel used in the LSL production. The influence of increasing or decreasing the wood fuel use did not have much influence on the impact category results except the RPRE indicator, which reflects the share of renewable fuels being used as a primary energy source.

#### **4. Conclusions**

Wood products are renewable and have much lower environmental impacts compared to fossil alternatives. This study performed an LCA to quantify the cradle-to-gate and cradle-to-grave environmental impacts of LSL products by following the guidelines of ISO 14000 and PCR. Also, three EoL options are compared which included landfill disposal (option 1: base case), burning to generate heat (option 2), and recovery and reuse of LSL products (option 3). Primary data was collected from manufacturers of LSL and the remaining data requirement were supplemented from literature. The functional unit was considered as 1 m<sup>3</sup> of LSL produced, used, and disposed of at the EoL. Irrespective of indicators, the cradle-to-gate stage contributed more than half towards LSL's cradle-to-grave environmental impacts. The cradle-to-grave GW impacts of LSL was 493 kg CO<sub>2</sub> eq/m<sup>3</sup> (~56% and 44% were from cradle-to-gate and gate-to-grave life cycle stages, respectively). In the cradle-to-gate stage of LSL, the hotspot was the resource extraction stage which included activities to produce logs as well as resins and wax. In the gate-to-grave, LSL transportation (A4) was the main hotspot mainly because of the long transportation distances from manufacturing sites to installation. Among the three LSL disposal options compared, the cradle-to-grave GW impacts and FFD of LSL in option 2 were negative and outperformed the other two disposal options. In the rest of the impact categories (OZD, SF, AC, and EU), option 3 (recovery and reuse of LSL) outperformed the other two disposal options. Moreover, EoL options 1 and 3 stored about 1,010 and 1,320 kg CO<sub>2</sub> eq carbon stored in the product and/or landfill, respectively. The long-term carbon storage value was about twice the cradle-to-grave GW impact of LSL. The quantity of adhesive used in LSL manufacturing influenced most of the impact indicators in sensitivity analysis results. Ensuring the optimal adhesive use in LSL manufacturing would improve LSL's environmental performance. Overall, this study showed that LSL had very low or negative GW impacts and carbon storage attributes would favor the wood products when substitution with other non-wood materials would be considered.

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#### **Author Contributions**

K.S. and R.B. came with the project and research idea; K.S. and R.B. designed the project and modeling approach; K.S. performed the modeling and analyzed the results; K.S., R.B, and M.P. reviewed the results. K.S., R.B, and P.K. developed the manuscript's structure and wrote the manuscript; all authors contributed to revising and editing the manuscript; and project administration and funding acquisition for the study was done by R.B.

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## Competing Interests

The authors declare no conflict of interest.

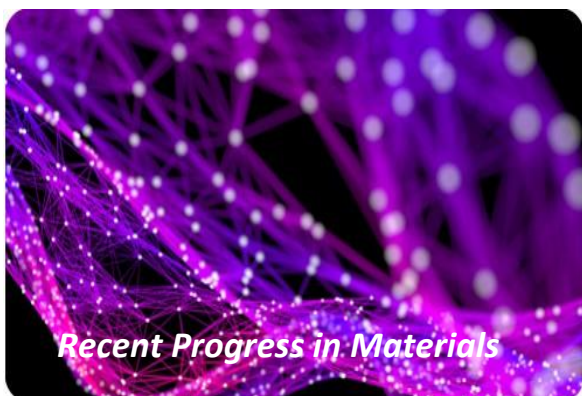
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