

Assessing the life-cycle environmental impacts of the wood pallet sector in the United States

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ABSTRACT

Wood pallets play a critical role in the movement and storage of goods worldwide. They are an important component in the complex global supply chain and used by almost every industry. It is therefore important to assess the environmental implications of the wood pallet supply chain and identify optimization strategies that can be implemented. In this paper, primary 2018 annual production data collected from U.S. pallet manufacturers were used to develop the first industry-average life-cycle inventory (LCI). A new functional unit was proposed to perform a more refined and accurate environmental life-cycle assessment of the wood pallet supply chain. Using the LCI data developed, a cradle-to-grave industry-average life-cycle impact assessment was performed. This novel approach quantifies environmental impacts of a generic multi-use pallet, including repair and remanufacturing. The total global warming impact was 10.4 kg CO₂e per 45.4 t of pallet loads of product delivered using wood pallets. The manufacturing stage contributed the most, about 35%, followed by the raw material supply stage. About 41% of total primary energy consumption was from renewable sources, with most sourced from biomass. Fossil fuels comprised about 52% of the total (225 MJ per functional unit) primary energy consumption. Total environmental impact was significantly affected by two main parameters: reference service life and load-bearing capacity. Pallet repair was also found to be an important component of the wood pallet supply chain, which has a low environmental footprint compared with the overall impact of a pallet and enables mitigation of overall impact by extending the reference service life. At end-of-life, common industry practices demonstrated substantial potential environmental benefits that can minimize overall environmental impact.

1. Introduction

Pallets are developed for efficient material handling and are used globally to store, transport, and handle goods. About 1.8×10^9 pallets are in service in the United States, and about 4×10^9 pallets are in service in the European Union (ADEQ, 2016; UNECE, 2016). There is a growing movement towards a low carbon future driven by consumers and governments; increasing concerns are causing companies to find strategies for improving their sustainability. Increasing interest in low-impact products with higher environmental performance requires producers to optimize their systems to improve their environmental performance. Wood pallet manufacturers have progressively looked for ways to assess and improve their environmental performance. Life-cycle assessment (LCA) is a widely accepted tool used to quantify the environmental impacts associated with a service or a product. LCA can be

used to understand and quantify the environmental impacts of wood pallets and assess potential areas of improvement in the supply chain.

Pallets are manufactured using various materials, including metal, plastic, corrugated, and composite, but wood pallets have the greatest market share, about 92% (Freedonia Group, 2020). Wood pallet LCAs are quite complex because of high variability in the wood species used, size, number of uses, load capacity, durability, and repairability of the pallets manufactured. Several LCA studies have evaluated wood pallet life-cycle impacts. Some studies used LCA methodology to explore environmental impacts of different handling conditions, reuse intensities, and end-of-life alternatives (Gasol et al., 2008; Tornese et al., 2018). Carrano et al. (2015) investigated the carbon implications of three different pallet management strategies, pooled, single-use, and multi-use, focusing on the carbon emissions. Several studies assessed the environmental performance of the wood pallet supply chain to identify

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hotspots and optimization strategies (Carrano et al., 2014; García-Durañona et al., 2016). García-Durañona et al. (2016) analyzed the environmental impact of sawnwood and pallet production and concluded that electricity used for thermal treatment was the major contributor to environmental impact and that the use of steel nails accounted for a large part of the impact from pallet manufacturing. The contribution of the end-of-life (EoL) stage was excluded in this study. LCA was also used to compare plastic pallets with wood pallets and to compare different wood material inputs (Anil et al., 2020; Bengtsson and Logie, 2015; Kočí, 2019; Mazeika Bilbao et al., 2011). Repair–remanufacturing of pallets is an important stage of the wood pallet supply chain, which allows pallets to get reused thus extend their service life. The environmental impacts of pallet repairs were also investigated using LCA, where both studies focused only on carbon implications (Park et al., 2018; Tornese et al., 2016). Tornese et al. (2016) also provided a linear optimization model that is used to understand the benefits of pre-emptive component repair. However, a more comprehensive approach was needed to cover the full function of a pallet along with repair–remanufacturing for a sector-wide analysis.

This unique study presents a complete environmental assessment of the wood pallet manufacturing and recycling sector in the United States. Although research on wood pallet LCA exists, a representative primary dataset based on extensive industry coverage was not available for wood pallets. Also, a more refined functional unit is needed to better describe how pallets are used so that improper comparisons are not made between pallets. In this study we used a representative industry-average dataset for wood pallets to perform a state-of-the-art LCA analysis, which entails methodology development with adaptations made to existing LCA studies, and a life-cycle inventory (LCI), which is crucial for LCA practitioners to perform high-quality evaluations of downstream products. This work (1) adds literature on a novel primary dataset of wood pallet production supply chain based on comprehensive industry-wide data and (2) presents an LCA methodology with a new proposed functional unit. Trip-based, load-based, or pallet-based functional units were used in previous studies. The purpose of a pallet is to handle, store, and transport cargo; therefore, we proposed a functional unit based on the overall load carried during the useful life of a pallet that is calculated using the trip-numbers and the specific load-carrying capacity of a pallet. This is significant because load-carrying capacity can vary depending on support and handling conditions, which can ultimately create inadequate comparisons between pallets. LCA methodology developed in this work formed the basis of the first product category rule

2. Materials and methods

Primary data were collected from new wood pallet and repair–remanufacturing facilities by surveying facilities throughout the United States. In this study, UL Environment product category rule (PCR) for wood pallets and LCA guidelines ISO 14040 and ISO 14044 were followed (ISO, 2006a, 2006b; UL Environment, 2019).

2.1. Goal and scope

The goal of this study is to provide a thorough analysis of wood pallet manufacturing in the United States by quantifying cradle-to-grave environmental impacts and identifying environmental hotspots in the supply chain for system improvement. An industry-average LCI was developed and a life-cycle impact assessment (LCIA) was performed.

The scope of this LCA included the life-cycle stages of wood pallet manufacturing starting from forest resource activities through end-of-life (EoL). The cradle-to-grave system boundary covered raw material acquisition and transportation, product manufacturing, repair/reuse, and EoL disposal of pallets (Fig. 1). The use phase includes transportation of goods and was left outside the system boundary because it is subject to high variability and uncertainty (UL Environment, 2019). However, scenario analysis was performed to identify the impact of various use phase transportation distances on the results. The analyses were done for multi-use pallets, which represent the primary market in the United States. Although wood pallets are manufactured in a variety of sizes and for a variety of functions, 1220- by 1020-mm pallets had the single highest share in the market in 2016 (Gerber et al., 2020). This design is referred to as “distribution” or “retail” style, also typically referred to as Grocery Manufacturers Association (GMA) pallets, and mainly used in the retail industry.

The functional unit (FU) selected for this study was 45.4 t of pallet loads of product delivered using wood pallets. In this study, the FU was developed to better represent the function of a wood pallet than in prior studies and allow results to be used as a more concise benchmark in the industry. The function of a wood pallet is to move goods, to stack and fit in racks, to be easily reached by pallet jacks and forklifts, and to function in automated warehouses. The number of pallets required to meet the FU was calculated using the reference service life (RSL) and load bearing capacity:

$$\text{Number of pallets required} = \frac{45.4 \text{ t of product delivered}}{\text{RSL} \left(\text{number of } \frac{\text{trips}}{\text{pallet}} \right) \times \text{Load bearing capacity} \left(\frac{\text{t}}{\text{trip}} \right)} \quad (1)$$

(PCR) for wood pallets. Finally, we demonstrate the application of the methodology and primary data developed using up-to-date secondary data, particularly for wood resources used, to evaluate the wood pallet supply chain.

An industry-average LCI was developed based on 2018 primary data collected from wood pallet manufacturing and repair–remanufacturing facilities throughout the United States. Environmental impact analysis and comprehensive scenario analysis were performed using LCA. This study addresses the environmental impacts associated with each life-cycle stage to provide a foundation for understanding and generating strategies for improving the environmental performance of the wood pallet supply chain. The results provide a sectoral benchmark as a basis of comparison for individual companies.

Because a pallet can be handled or stored in a variety of ways, load-bearing capacity can vary depending on use. In this case, the FU was calculated using the “racked across the length (RAL)” load-bearing capacity, consistent with the UL PCR (UL Environment, 2019). RAL specifies that the pallet is supported only at its ends, either in a rack system or conveyor, instead of racked across width, which specifies that the pallet is supported only at its edges.

The wide range of pallet designs available in the market can have quite different design specifications depending on intended use. The type and amount of wood species used and technical design result in different loading capacities and durability of a pallet. The durability and service life of a pallet are highly dependent on its design and handling and loading conditions. The stringer class and block class assembly are the two main categories of wood pallet designs used in the United States. For this industry-average LCA, four wood pallet types were selected for

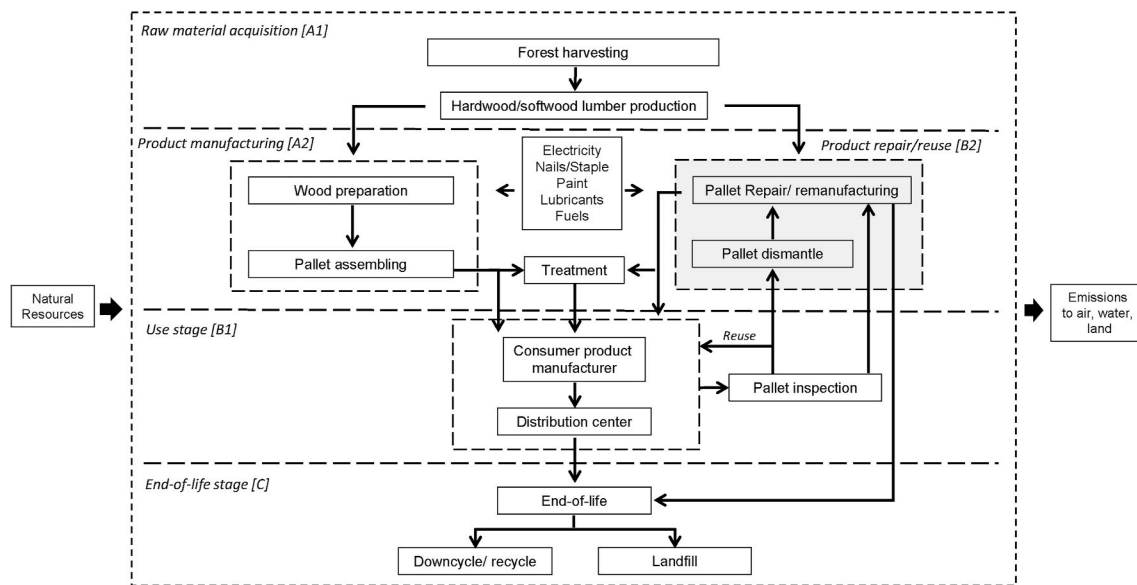


Fig. 1. The general schematic representation of wood pallet life-cycle.

Table 1
Specifications, predicted reference service life (RSL), and functional units of wood pallet designs.

Pallet type	Overall predicted RSL (trips)	Load capacity ^a (kg)	Average m ³ per pallet	Average weight 12% moisture content (kg)	Number of pallets required to transport 45.4 t of product
Stringer light duty	10	454	0.026	14.1	10.0
Stringer heavy duty	38	680	0.034	18.6	1.75
Block light duty	16	680	0.034	20.0	4.07
Block heavy duty	66	1134	0.057	33.1	0.61

^a Given as Racked “Across the Length”, it should also be noted that PDSTTM incorporates a safety factor of 2–2.5 in all loading capacity estimations.

Table 2
Specifications and functional unit of the industry-average wood pallet for the United States.

Specification	Value
Average weight (kg) at 12% moisture content	18.57
Average weight (oven-dry kg)	16.58
Average m ³ per pallet ^a	0.033
Load supported during the life of the pallet (racked “across the length”) (kg)	21,310
Number of pallets required to transport 45.4 t pallet loads of product (FU)	2.13

^a 2.36 m³ per 1000 actual board feet.

the analysis: the stringer “light duty” (LD), stringer “heavy duty” (HD), block LD, and block HD pallets ([Table 1](#)). To quantify the average number of trips until the first repair, the FasTrack test protocol developed by Virginia Tech was used ([VT, 2018](#)). Each pallet type was tested by the Center for Packaging and Unit Load Design of Virginia Tech University (Blacksburg, Virginia, USA) using 30 replicates ([VT, 2019](#)). After each repair, RSL was assumed to increase by the number of uses to

the first repair; the pallet was assumed to be fully restored to its former condition. See “Section 3.1.1. Reference Service Life” of UL Environment PCR for wood pallets for RSL calculation instructions with repairs (UL Environment, 2019). The industry-average pallet specifications were quantified based on 2016 production data, where 78% of the pallets were stringer pallets and 22% were block pallets (Table 2) (Gerber et al., 2020). It was assumed that 50% of the pallets produced were LD for both the stringer and block pallets.

Although it is generally understood that wood pallets may experience several repairs during the use phase, in this study it was assumed that each pallet was repaired for a single time before it reached the EoL.

2.2. Description of the wood pallet production system

The cradle-to-grave life-cycle stages of wood pallets consist of sourcing of raw material, raw material transportation, product manufacturing, use and repair, and EoL. The system boundary starts at raw material acquisition. Site preparation and planting seedlings, forest management (fertilization and thinning), harvesting, transportation of sawlogs to the lumber manufacturing facility, and lumber production occur at this stage. Pallet facilities predominantly received lumber that is either precut, rough green, and/or kiln-dried. Softwood (SW) and hardwood (HW) products received are mostly green (freshly cut), with a smaller amount of dry SW lumber. Very small amounts of plywood and oriented strandboard (OSB) were reported by some facilities.

The wood pallet manufacturing stage can be divided into three main processes: wood preparation and board shaping, assembly/nailing, and supplementary processes. Supplementary processes include stamping, utilities, internal transportation, and optional processes such as treatment and painting. The first step of production is cutting the lumber to the desired size and notching, followed by the assembly unit process. Additional processes take place depending on specifications of the pallet produced. Treatment may be applied if pallets are used for international consumption or by customer request. Heat treatment is the commonly used method, but both heat and chemical treatments comply with International Standards for Phytosanitary Measures No. 15 (ISPM 15) (IPPC, 2009). Use and repair stages follow the manufacturing stage. EoL is the final stage, where unusable pallets that cannot be further repaired are dismantled. About 37.3% of the boards from the dismantled pallets were used for repairs and remanufacturing. The rest of the boards were ground and repurposed as mulch, fuel, or animal bedding. Based on data from [Shiner \(2018\)](#), after the use phase, about 13% of pallets produced

were received by solid waste disposal facilities, but only about 5% of this total were landfilled because of diversion practices (Shiner, 2018).

In this study, the cut-off (recycled content) approach was used for the impact assessment analysis, where no benefits were claimed for recycled material at the EoL. Scenario analyses were performed by modeling the system with different EoL approaches. The avoided burden approach (or EoL recycling approach) was used for scenario analysis (Frischknecht, 2010; Tillman and Baumann, 2004).

2.3. Data inventory

The industry-average LCI was developed using weighted-average data collected on the wood pallet supply chain. Primary (foreground) data were collected from U.S. wood pallet manufacturers using surveys. Surveys were sent to new pallet manufacturing and recycled–remanufactured pallet producers. Primary data were collected for 2018. Various site visits were conducted over the course of the study. The total annual pallet production of the participating facilities was about 49,790,000 for new pallets and 37,950,000 for repaired–remanufactured pallets, representing about 10% and 12% of total U. S. production, respectively. Data were received from 40 facilities distributed across the United States for new pallet manufacturing. Of the 40 facilities responding, 18 were from the South, 10 from the Northeast, 9 from the Midwest, and 3 from the West.

Secondary data sources used for the background processes included the ecoinvent and DATASmart (US EI 2.2) databases, and LCA was conducted using SimaPro v9 software (LTS, 2019; PRé Consultants, 2019; Wernet et al., 2016). The wood material LCIs were retrieved from the Consortium for Research on Renewable Industrial Materials (CORRIM) datasets (Hubbard et al., 2020; Milota, 2015a, 2015b; Oneil et al., 2010; Puettmann et al., 2016a, 2016b, 2020). See Table S1 in the Supplementary Data for the list of secondary data sources used, including the electrical grid mix used in this analysis.

The weighted average wood material inputs to pallet manufacturing are provided in Table 3, and transportation data are provided in Table 4. About 19% of the lumber used was precut lumber, of which about 45% was HW lumber. The process required 1.18 m³ of wood material to make 1 m³ of wood pallet. The electricity consumption for the precut lumber at the raw material supply stage was accounted for and was adopted from Bergman and Bowe (2012).

Environmental inputs and outputs for the gate-to-gate wood pallet manufacturing stage are provided in Table 5. Mass balance on wood was performed on a per-facility basis to assess data accuracy. The total product mass, pallet output, was calculated based on the volume of wood that constitutes a pallet. Pallets are produced in a variety of sizes, and it is complex to quantify total output for manufacturers producing a wide variety of products. It was assumed that a generic wood pallet constituted 0.035 m³ of wood material for the facilities where pallet size data was not reported by the manufacturer. Diesel and propane used for trucks and forklifts during internal transportation were included in the inventory. About 21% of total pallet production surveyed were heat-treated.

Table 3

Wood resources used per m³ wood pallet manufactured.

Wood material	Weighted Average (m ³)	By percentage (%)
HW lumber	4.56E-01	38.80%
SW lumber (green)	2.10E-01	17.87%
SW lumber (dry)	4.99E-01	42.46%
Plywood	9.41E-03	0.80%
OSB	7.40E-04	0.06%
Total	1.18E+00	100.0%

Table 4

Weighted-average transportation by mode for materials to wood pallet manufacturing facility per m³ pallet manufactured.

Material	Unit	Mode	Weighted Average
Precut HW Lumber	tkm	Truck	5.33E+01
Precut SW Lumber	tkm	Truck	1.56E+02
HW Lumber	tkm	Truck	6.19E+01
SW Lumber	tkm	Truck	1.60E+02
SW Lumber	tkm	Rail	3.14E+01
Plywood	tkm	Rail	5.66E-02
Plywood	tkm	Truck	7.99E-01
OSB	tkm	Truck	3.75E-02

2.4. Life cycle impact assessment

The life-cycle impact assessment (LCIA) was performed by using the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) 2.1 method (Bare, 2011). Six impact categories covered in the TRACI method were examined and presented. These include global warming (GW (kg CO₂-eq)), acidification (kg SO₂-eq), eutrophication (kg N-eq), ozone depletion (kg chlorofluorocarbons-11-eq), photochemical smog (kg NO_x-eq), and fossil fuel depletion (MJ surplus). The total primary energy input was quantified based on the LCI results using the Cumulative Energy Demand (CED) method published by ecoinvent. The method is based on lower heating values (LHV). The mass allocation and the unit process modeling approach was followed while modeling the LCA.

2.5. Sensitivity analysis

A wide range of parameters may affect the resulting environmental impact of a wood pallet. A comprehensive sensitivity and scenario analysis was performed to explore how the selected input parameters and different management strategies influence environmental impact. In addition to parameter-based sensitivity, scenario-based uncertainty analysis was performed with respect to EoL management used and use phase transportation distance.

Parameter sensitivity was tested via contribution to the GW impact for 20% variation in four key parameters. Selected parameters included electricity input, amount of fasteners used, amount of wood material input to the wood pallet manufacturing system, and fuel used in internal transportation.

The EoL scenario analysis was performed to provide more information on potential environmental benefits and burdens of different EoL pathways (Table 6). The data collected from the facilities were used as the base scenario for the EoL management of a wood pallet. For the base case scenario, EoL pathways were reported as follows: 5% of pallet material was sent to landfill, 37.3% was reused as boards, 17.3% was sold as fuel, and 40.4% was sold as mulch and animal bedding. The portion of the coproducts (mill residues) from pallet manufacturing that is used as fuel was also included as credit in the substitution scenarios. Environmental credits of coproducts generated at lumber production facilities were not taken into account. For the last three alternative scenarios, about 50% of the pallet at the EoL was assigned to mulch and animal bedding with no assumed environmental benefits and burdens and the rest was assigned to alternative handling options: reused (dismantled) boards, fuel, and landfill disposal. For the fuel scenario, the effect of the ratio of the wood pallet that is diverted to fuel to substitute fossil fuels in the market (avoided product) on the resulting GW impact was investigated. Natural gas boilers used in lumber drying were assumed to be substituted with wood boilers. Boiler efficiencies were considered in the analysis. The influence of boards reused from dismantled pallets to replace virgin lumber input on the resulting GW impact was quantified. The GHG implications of an increased portion of pallets sent to landfills were also examined. The substitution scenarios included the environmental benefits of the portion of coproducts that

Table 5

Inputs and outputs for the wood pallet manufacturing supply chain for 45.4 t of pallet loads of product delivered.

	Unit ^{a,b}	Weighted Average	Allocation
Wood preparation and board shaping			
Products—coproducts			
Wood, at pallet facility	p	2.13E+00	82.3%
Sawdust	OD kg	3.08E+00	6.8%
Hogged material	OD kg	1.95E+00	4.3%
Wood Chips	OD kg	2.33E+00	5.2%
Scrap Wood	OD kg	1.13E-02	0.0%
Shavings	OD kg	6.18E-01	1.4%
Materials—fuels			
Wood resources, average, at pallet facility	m ³	8.30E-02	
Greases	g	2.48E-01	
Motor Oil	g	7.23E-01	
Hydraulic fluid	g	1.52E+00	
Lubricating fluid	g	1.00E+00	
Plastic wrapping	g	6.37E-01	
Cardboard packaging	g	4.79E-01	
Natural Gas	L	2.64E+01	
Diesel	L	7.57E-02	
Gasoline	L	7.71E-04	
Liquefied petroleum gas	L	3.47E-03	
Wood fuel	OD kg	1.96E-03	
Diesel, forklift	L	2.35E-02	
Diesel, truck	L	1.03E-02	
Gasoline, truck	L	1.05E-04	
Propane, forklift	L	7.42E-02	
Electricity			
Electricity	kWh	1.56E+00	
Waste			
Steel scrap	g	4.18E+01	
Plastic wrap	g	9.80E-01	
Cardboard packaging	g	1.06E+01	
Hydraulic Fluid	g	1.60E-01	
Motor Oil	g	2.33E-02	
Grease	g	3.42E-03	
Lubricants	g	2.09E+00	
Pallet assembly-nailing			
Products—coproducts			
Wood pallet, assembled	p	2.13	100.0%
Materials—fuels			
Wood boards, at pallet facility	p	2.13E+00	
Fasteners	G	5.58E+02	
Greases	G	2.32E-01	
Motor Oil	G	6.20E-01	
Hydraulic fluid	G	2.42E+00	
Lubricating fluid	G	1.07E+00	
Plastic wrapping	G	1.46E-02	
Cardboard packaging	G	1.40E-01	
Natural Gas	L	1.17E+01	
Liquefied petroleum gas	L	3.47E-03	
Diesel	L	5.82E-04	
Gasoline	L	7.10E-04	
Wood fuel	OD kg	1.96E-03	
Diesel, forklift	L	2.35E-02	
Diesel, truck	L	1.03E-02	
Gasoline, truck	L	1.05E-04	
Propane, forklift	L	7.42E-02	
Electricity			
Electricity	kWh	6.96E-01	
Waste			
Cardboard packaging	G	3.549	
Hydraulic Fluid	G	0.160	
Motor Oil	G	0.023	
Grease	G	0.003	
Lubricants	G	2.087	
Treatment-stamping-painting			
Products—coproducts			
Wood pallet final, pallet facility	P	2.13	100.0%
Materials—fuels			
Wood pallet, assembled	P	2.13E+00	
Natural Gas	L	4.15E+00	
Liquefied petroleum gas	L	5.56E-02	

Table 5 (continued)

	Unit ^{a,b}	Weighted Average	Allocation
Fungicide	G	1.12E-01	
Paint	G	4.90E+00	
Ink	G	1.62E-03	
Electricity			
Electricity	kWh	0.05	

^a Unit “p” refers to amount of wood used to produce 2.13 pallets.

^b Oven-dry (OD) kg.

Table 6

A review of the end-of-life scenarios analyzed for wood pallets.

Scenario	EoL assumptions	Environmental benefits considered
Base case	5% was landfilled, 37.3% was reused as boards, 17.3% was sold as fuel and 40.4% was sold as mulch and animal bedding	- dismantled boards replace virgin lumber coming in - co-products from wood pallet manufacturing and 17.3% of the pallet at the EoL used as wood fuel in wood boilers replacing natural gas
Cut-off	5% was landfilled, 37.3% was reused as boards, 17.3% was sold as fuel and 40.4% was sold as mulch and animal bedding	No benefits
50% dismantle	50% was reused as boards, 50% was sold as mulch and animal bedding	- dismantled boards replace virgin lumber coming in - co-products from wood pallet manufacturing used as wood fuel in wood boilers replacing natural gas
50% fuel	50% was sold as fuel, 50% was sold as mulch and animal bedding	co-products from wood pallet manufacturing and 50% of the pallet at the EoL used as wood fuel in wood boilers replacing natural gas
50% landfill disposal	50% was landfilled, 50% was sold as mulch and animal bedding	co-products from wood pallet manufacturing used as wood fuel in wood boilers replacing natural gas

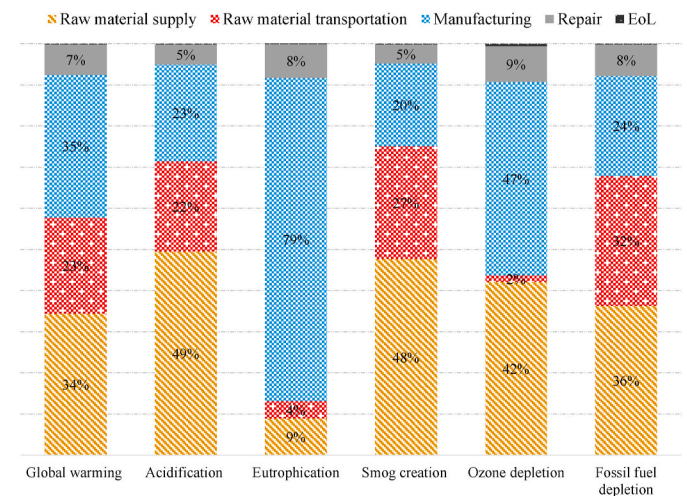


Fig. 2. Cradle-to-grave life cycle impact contribution analysis for 45.4 t of pallet loads of product delivered.

are reported by the facilities to be sold as fuel. Environmental burdens of grinding the pallet parts used as fuel at the EoL were accounted for, and electricity consumption for the grinder was assumed to be 13.3 kWh/OD t (Spinelli et al., 2012). The transportation of wood fuel to users was

taken into consideration and was assumed to be 50 km.

3. Results

3.1. Life cycle impact assessment

The cradle-to-grave GW impact was about 10.4 kg CO₂e per 45.4 t of pallet loads of product delivered (see Table S2 in the Supplementary Data). The LCIA results showed that raw material supply and manufacturing stages were the major contributors to the impact categories investigated (Fig. 2). The contribution analysis showed that the GW impact was dominated by manufacturing and raw material supply stages, with 3.60 and 3.58 kg CO₂e per FU, respectively. The GW impact at the manufacturing stage was dominated by wood preparation and board shaping process, which can be traced to the electricity consumed. It is followed by the assembly/nailing process, with most impact coming from fastener use. The manufacturing stage accounts for about 79% of the eutrophication potential because of the electricity consumed at the manufacturing stage. The contribution of the repair stage to GW impact was only about 7%. The repair stage tends to use manual labor with power tools, although a few facilities have started to incorporate automation in the disassembly of old pallets.

The primary energy use assessment was performed using the CED method (Table 7). Renewable biomass energy comprised about 40% of the total primary energy use of 225 MJ/FU, with most (99%) from raw material supply stage. At this stage, biomass refers to wood fuel burned in wood boilers for drying at lumber manufacturing. For EoL stage, energy use was minor compared to other stages.

3.2. Scenario and sensitivity analysis

The impact of use phase transportation distance on the resulting GW impact is presented in Fig. 3. Use phase transportation is the distance goods travelled on pallets. The influence of changing use phase transportation from 250 km to 1250 km on the GW was investigated along with its effect on the contribution of life-cycle stages to the total GW impact. An increase in transportation distance from 250 km (minimum case) to 1250 km (maximum case) results in 35% increase in the total GW impact. Contribution of the use phase started to outweigh the other stages on GW impact when transportation distance exceeded 950 km, where its contribution exceeded 25%.

There are several practices performed by the wood pallet industry at product EoL. This study evaluated these practices for their environmental impact and potential benefits. The LCIA results for two different EoL allocation methods, cut-off and substitution, are presented in Fig. 4. The base case scenario for EoL pathways was reported as 5% to landfill, 37.3% reused as boards, 17.3% sold as fuel, and 40.4% sold as mulch and animal bedding. All substitution scenarios include credits from fuel substitution of the coproducts generated at the manufacturing stage. About 27% of coproducts generated at new pallet manufacturing facilities was sold as wood fuel. When the influence of different EoL pathways on the total GW impact was examined, the potential credits from the fuel scenarios had the greatest benefits. For fuel case, 50% of pallet waste was used as boiler fuel substituting natural gas. At the boiler, natural gas and wood fuel were assumed to be combusted with 80% and

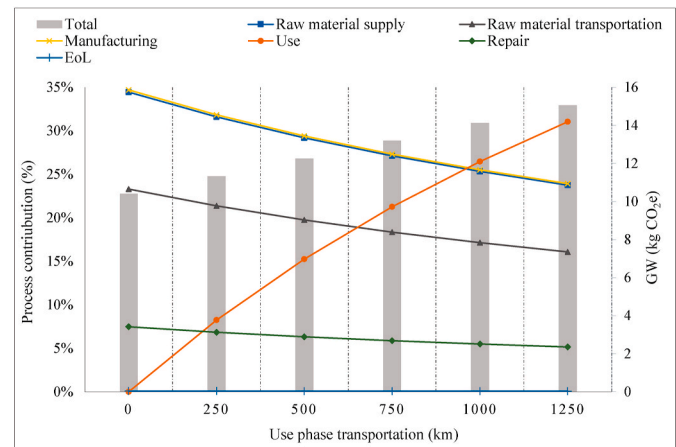


Fig. 3. Use phase scenario analysis. The left axis corresponds to the line plots showing the process contribution and the right axis corresponds to the column plot showing the total GW impact of 45.4 t of pallet loads of product delivered with wood pallets.

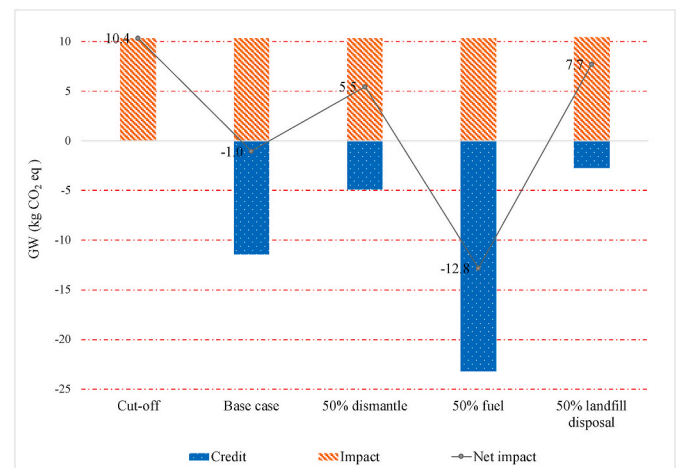


Fig. 4. End-of-life scenario global warming impact evaluation per functional unit (the remaining 50% of the pallet at the EoL was assigned to mulch and animal bedding with no assumed environmental benefits for 50% dismantled, fuel, and landfill disposal cases).

74% efficiency, respectively (Forest Products Laboratory, 2004; U.S. Environmental Protection Agency, 2008). For the dismantled pallet case, the reuse of the recovered pallet boards resulted in a -2 kg CO₂e GW impact, whereas the rest of the credit was from coproduct fuel substitution. Recovery of pallet boards replacing virgin wood had benefits in other impact categories as opposed to fuel substitution. The dismantled pallet scenario resulted in a 26%–30% reduction in ozone depletion, smog, and acidification impact categories (see Table S3 in the Supplementary Data).

Load-carrying capacity and number of repairs are important

Table 7

Cradle-to-grave primary energy analysis of 45.4 t of pallet loads of product delivered with wood pallets, mass allocation.

Use of Primary Resources		Total	Raw material supply	Raw material transportation	Manufacturing	Repair	EoL
Renewable primary energy	MJ, NCV ^a	2.61	1.2	0.05	1.17	0.19	0
Renewable primary energy biomass	MJ, NCV	89.59	88.53	0.01	0.31	0.75	0
Non-renewable primary energy (fossil)	MJ, NCV	117.26	39.23	30.3	38.48	9.11	0.14
Non-renewable primary energy (nuclear)	MJ, NCV	15.04	7.04	0.44	6.47	1.09	0.01
TOTAL	MJ, NCV	224.50	136.00	30.80	46.43	11.14	0.15

^a Net calorific value (NCV).

Table 8

Influence of number of repairs and load carrying capacity on the GW impact from cradle-to-grave, mass allocation.

Parameter	Number of pallets required to transport 45.4 t pallet loads of product (FU)	GW impact (kg CO ₂ eq)	Impact of repair stage
Number of repairs			
1- repair	2.13	10.4	1.01
2- repairs	1.45	7.4	0.78
Load carrying capacity			
20% increase	1.77	7.8	

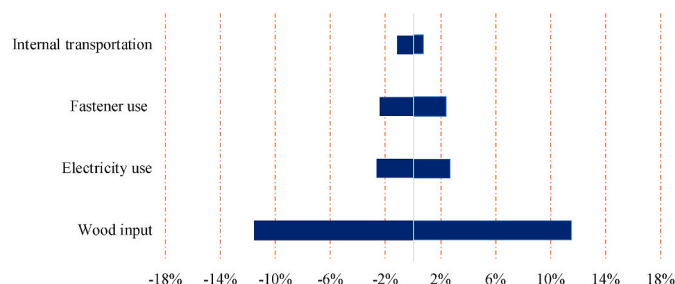


Fig. 5. Sensitivity of parameters on overall impact for 45.4 t of pallet loads of product delivered.

parameters. Load-carrying capacity directly affects the FU; number of repairs affect FU indirectly because RSL increases with each repair. Scenario analyses were performed to evaluate the influence of number of repairs and load-carrying capacity on overall GW impact. Results showed that a notable decrease may be achieved through increased number of repairs, whereas the impact from the repair stage itself did not have a major contribution to the resulting GW impact (Table 8). Given a single repair, a 20% increase in load-carrying capacity resulted in a 17% decrease in GW impact. The resultant impacts of these two parameters indicate that future improvements of environmental performance for the wood pallet industry can be found here.

The parameter sensitivity analysis for 20% variation in four key parameters was performed to measure the impact of fluctuations on GW impact and is presented in Fig. 5. Wood material input had the highest influence, resulting in about 12% variance in the resulting GW impact. Contrarily, the other three parameters had a minor influence on GW impact, ranging from 1% to 3%.

4. Discussion

This study presented a cradle-to-grave environmental evaluation of the wood pallet manufacturing and recycling sector using industry-average data representative of the United States. The contribution analysis showed that raw material supply and manufacturing life-cycle stages had the highest contribution to selected environmental indicators. Production of lumber and precut lumber at raw material supply phase constituted about 34% of total GW impact, where electricity used in sawing and (kiln) drying was a major contributor to the GHG emissions at lumber production (Bergman and Bowe, 2012; Hubbard et al., 2020; Milota, 2015a). At wood pallet manufacturing stage, fastener production and electricity use were the main drivers for the GW impact. Similarly, García-Durañona et al. (2016) showed that steel nail use at the manufacturing stage was one of the major contributors to most impact categories. Repair and EoL stages had the lowest impact, which is consistent with the analysis performed by Gasol et al. (2008). Raw material transportation, with a 23% contribution, also had an important role in GW impact. Selection of closer lumber suppliers to decrease the raw material transportation distance could help to mitigate GHG

emissions. GHG mitigation reduction strategies are becoming increasingly important as the Earth warms. The use of low-carbon footprint wood products are one mitigation strategy (Bergman et al., 2014). Wood pallets fit into this category based on their carbon footprint.

Load-carrying capacity is one of the major parameters that affect the FU of a pallet. It is important to note that the FU was calculated using RAL load-carrying capacity. RAL is the most aggressive support condition a pallet may encounter, which means that a minimum estimated load-carrying capacity was used. The sensitivity analysis showed that the change in load-carrying capacity has a substantial influence on resulting GHG emissions. Pallet load was also found to be an important parameter by Carrano et al. (2015) because of its effect on pallet service life, which affects overall environmental impact, especially global warming. Through the new specification of load-bearing capacity for a specific application, this FU classifies pallets so that lower capacity pallets are now properly compared to higher capacity pallets.

Overall, the resulting cradle-to-grave GW impact was 10.4 kg CO₂e per FU. The LCIA results are not directly comparable with previous studies, because of the differences in functional unit developed and used for impact assessment. This approach proposes to model environmental impacts as accurately as possible and provide a benchmark for future analysis performed by the industry and LCA practitioners.

Scenario analysis showed that repairing used pallets bringing them back into service can improve sustainable management of wood pallets because higher circulation mitigates environmental impacts of the wood pallet supply chain. The contribution of the repair and/or remanufacturing stage of wood pallets to GW impact was minor. Furthermore, more repairs resulted in a significant decrease in environmental impacts. It is important to note that after each repair, the pallet was assumed to be fully restored to its former condition so the RSL was assumed to increase by the number of uses accumulated before the first repair. The single repair assumption used in this work was a conservative assumption because industry standard wood pallet modeling software, Pallet Design System™ (PDS), shows that wood pallets are typically repaired more than once. Performing an analysis using field data for the overall RSL and number of repairs a wood pallet undergoes during its whole life cycle will provide a more accurate analysis of the environmental impacts.

For wood pallets, the contribution of the use phase is dependent on the distance that the goods are transported. When products are delivered over longer distances, using a lightweight material may help reduce overall impact. Performing product-specific analysis is necessary because using different specifications may affect design parameters and consequently the FU. This may shift the environmental burden from one life-cycle stage to another.

When potential environmental benefits are considered, use of pallet wood at the EoL as an energy source to replace natural gas at boilers was the most environmentally beneficial case. At primary wood products facilities, natural gas and wood-fired boilers are typically used for wood drying, whereas secondary wood product facilities mainly use natural gas boilers due to lack of wood coproducts (mill residues) generated (Puettmann et al., 2010; Puettmann and Milota, 2017). Similarly, Puettmann and Milota (2017) showed that GW impacts were significantly lower when wood-fired boilers were used instead of natural gas boilers. In addition to fuel benefits, environmental benefits in the other impact categories can be achieved by substituting incoming virgin wood with dismantled pallet parts.

5. Conclusions

This is the first effort to generate industry-average wood pallet data and estimate the environmental impact of an average wood pallet used in the pallet sector in the United States. The cradle-to-grave environmental impact of the wooden pallet supply chain was quantified using a new primary dataset generated, up-to-date secondary data, and a unique functional unit. The results can be used by the wood pallet industry for

environmental benchmarking and by LCA practitioners for downstream supply chain analysis. The industry-average environmental assessment of wood pallet manufacturing in the United States showed that manufacturing stage and raw material supply stage had the highest and second highest, respectively, contributions to GW impact. These two stages were again the major contributors to other environmental impact categories.

The cradle-to-grave environmental assessment of an industry-average wood pallet is complicated by high variability of design parameters and variety of pallet types that exist in the market. It is important to use pallet-specific data for an accurate assessment of the environmental profile for the pallet type investigated.

The sensitivity analysis and scenario analysis showed RSL and load-bearing capacity are the key parameters that can be used to increase overall environmental performance of the wood pallet supply chain. Pallet repair is an important component of the wood pallet supply chain because it can be used to lengthen the RSL of a pallet. The repair stage itself has a low environmental footprint, and pallet repairs can help mitigate GHG emissions by increasing pallet service life.

It has been shown that proper and sustainable management practices performed by the industry at product EoL might help mitigate resulting cradle-to-grave environmental impacts. The EoL pathways may lead to significant environmental benefits. Major reductions in GHG emissions can be achieved by substituting natural gas with wood fuel generated at the EoL. It is important to have a holistic approach by considering the possible shift of environmental burdens. Fuel substitution results in great benefits in GW impact but has minor benefits in other impact categories. The GHG benefits of avoided virgin wood through reused (dismantled) boards were minor, but benefits were achieved in all other impact categories. This study provides a foundation for ongoing sustainability efforts of the wood pallet sector through GHG mitigation.

Because each pallet design has many variables that may affect the sensitive parameters detected (e.g., load-carrying capacity, reference service life, repairability), performing LCA specific to the pallet design investigated can lead to a better pallet selected for its environmental implications. In addition, it is important to be aware of potential burden shifts between different life-cycle stages and between different impact categories. This comprehensive assessment illuminates these effects through detailed analysis and interpretations.

CRedit authorship contribution statement

S. Alanya-Rosenbaum: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **R.D. Bergman:** Conceptualization, Methodology, Investigation, Resources, Writing – review & editing, Supervision, Project administration. **B. Gething:** Conceptualization, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2021.128726>.

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