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Life cycle assessment of the wood pallet repair and remanufacturing sector in the United States

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Abstract: Wood pallets are ubiquitous products that can be recovered and reused to enhance their service life and environmental performance. Repair/remanufacturing has an important role in extending the service life of the wood pallet. To quantify environmental performances of wood pallet reuse, this study developed representative life cycle inventory data for pallet repair/remanufacturing in the United States based on comprehensive industry-wide production data for 2018. A gate-to-gate life cycle assessment covering raw material supply, raw material transportation and pallet repair/remanufacturing showed that repair/remanufacturing often had the highest impacts, including primary energy consumption at 5.09 MJ and global warming impact at 0.355 kg CO_2 eq per repaired/remanufactured pallet. Electricity consumed onsite followed by nail input and the fuel used by forklifts during the manufacturing drove much of the impacts on the environment. The results of this study provide valuable information on the repair/remanufacturing impacts, allowing quantification and evaluation of the recovery stage on the overall environmental performance of wood pallets. © 2022 Society of Chemical Industry and John Wiley & Sons, Ltd.

Key words: wood pallet; environmental performance; reuse; repair; remanufacturing

Introduction

Pallets are a key component of the complex global supply chain. Vast numbers of pallets primarily made from wood are used for global shipping and storing a variety of goods and products. There are an estimated 1.8 billion pallets in service in the United States, 92% of which are made from wood.[1–3] The wood pallet and container manufacturing industry in the United States has a direct and indirect impact on more than 170 000 jobs and generates ~$31 billion of economic impact.[4] The wood pallet industry has continued to improve its resource efficiency by diverting pallets from landfills, with less than 5% now being landfilled at municipal solid waste facilities and 95% being repurposed.[5]

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Evaluating supply chains can show how and where to improve the logistics of the wood pallet sector, especially for recovery and reuse.

There is an increasing movement toward extending the service life of wood pallets through repairing and remanufacturing them after their first use. Therefore, the recovery of wood pallets is becoming more common in the United States and worldwide. Pallet repair refers to a process of revitalizing pallet component connections, removing and replacing broken blocks and boards and splinting broken stringers, or plugging deck boards and runners, so that the pallet can maintain its strength and structure. Pallet remanufacturing refers to the process of building pallets out of reclaimed parts or components from used pallets that have been dismantled.[6] In the United States, about 39% of the 839 million wood pallets produced in 2016 were repaired/remanufactured pallets.[7] This trend is consistent with that in other countries like the United Kingdom, where the number of repaired pallets surpassed new pallet production in 2016.[8] Manufactured primarily in rural forested communities, the supply chain for wood pallets is rather complex because of their durability, the high number of wood species used and the size, many uses, load capacity and repairability (reuse) of the pallets manufactured. All of these differences must be investigated when evaluating the life cycle environmental impacts of wood pallet reuse to enhance the environmental performance of the supply chain.

To identify these impacts of wood pallet reuse, life cycle assessment (LCA) methods can be used at different steps in the process.[9,10] LCA is a comprehensive tool used to assess the environmental implications of products and services throughout their life cycles.[11,12] According to International Organization for Standardization (ISO) 14040,[11] an LCA study consists of four phases: (1) goal and scope definition; (2) life-cycle inventory (LCI); (3) life-cycle impact assessment (LCIA); and (4) interpretation. At the LCIA phase, the potential environmental impacts of the system investigated are evaluated, which originate from the inputs and outputs identified in the LCI phase. Several LCA studies have been performed to evaluate the wood pallet life cycle impacts of repair. Park *et al.*[13] looked at the cradle-to-gate global warming (GW) impact of a repaired pallet but did not account for the transportation emissions of upstream raw materials, e.g. pallets, lumber, etc. Carrano *et al.*[14] calculated the GW impact of the refurbishment processes for a wood pallet throughout its life cycle, including multiple repairs and multiple transportation steps for pallet recovery. Tornese *et al.*[15,16] investigated wood pallet repair but only focused on GW impact. Therefore, a more inclusive approach is needed to cover the full function and life cycle environmental impacts of a repaired/remanufactured pallet as part of a sector-wide analysis.

As firms set goals to be more sustainable, a full understanding of the environmental impacts of their pallet operations becomes critical. The objective of this study was to evaluate the life cycle environmental impacts of wood pallet repair/remanufacturing. A unique industry-average LCI dataset representative of the whole US repaired/remanufactured wood pallet sector was developed for this analysis. The outcomes of this study are useful for improving the quality of future LCAs for systems using repaired/remanufactured pallets while covering all critical impact category measures including GW and primary energy consumption. In addition, this study helps to determine the environmental hotspots of gate-to-gate repaired/remanufactured pallet systems by identifying sources of environmental burdens in the product system and pointing out the potential improvements.

Materials and methods

Goal and scope definition

The goal of this study was to quantify the environmental impacts of wood pallet repair/remanufacturing in the United States. It is recognized that repaired and remanufactured pallets are different from each other, but for the purposes of this study they were treated as the same in order to evaluate the overall environmental impacts of this segment of the wood pallet industry. For this purpose, a gate-to-gate industry-average LCI was developed and an LCIA was performed. The LCI was developed using the primary data collected from repair/remanufacturing facilities spread throughout the United States through a survey questionnaire for the year 2018.[10]

The scope of this LCA included the gate-to-gate life cycle stages. The gate-to-gate system boundary covered raw material supply, raw material transportation (i.e. transportation of lumber to the repair/remanufacturing facility, and pallet collection/transportation) and pallet repair/remanufacturing operations (Fig. 1). The gate-to-gate LCA system boundary excluded the distribution, use and disposal phases. Two sources of wood raw material were reported by the wood pallet repair/remanufacturing facilities, i.e. recovered wood pallets and lumber. The production of lumber is part of the raw material supply life cycle stage. This stage consists of forestry operations (i.e. site preparation and planting seedlings, fertilization and thinning, tree harvest, the transportation of saw logs to the lumber manufacturing facility and lumber production). The other

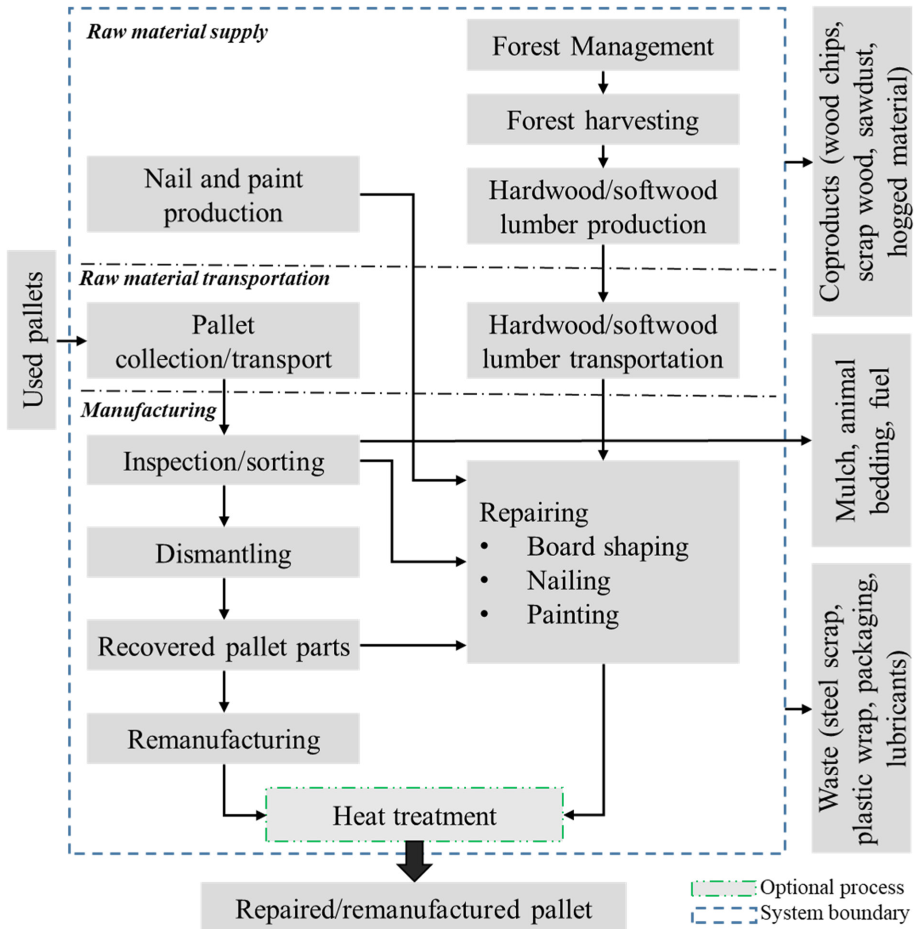

Figure 1. System boundaries of the wood pallet repair/remanufacturing product system.

major raw material input (i.e. used pallets) was reported to be collected from retailers and transported to repair/remanufacturing facilities. It was assumed that the pallets recovered by the repair/remanufacturing facilities came with zero environmental burdens except for their transportation to the facility. The second life cycle stage (i.e. raw material transportation) covers the transportation of the lumber and recovered pallets to repair/remanufacturing facilities.

At the pallet repair/remanufacturing facilities, inspection and sorting are conducted to determine the next processing steps for the recovered pallets. Not all of the recovered pallets require processing; a percentage are reused as they are (i.e. without repair) and returned to service. These pallets and impacts were still considered as part of the analysis. Most of the remaining recovered pallets are processed into repaired and remanufactured pallets. If pallets of popular sizes cannot be repaired or reused, they are typically dismantled and the components are mostly used for repair/remanufacturing. Repaired pallets (i.e. recycled pallets) are produced by repairing damaged pallet components using new wooden boards or reclaimed boards retrieved from dismantled pallets. Remanufactured pallets are completely rebuilt using recycled components and parts from dismantled pallets. The repair/remanufacturing stage comprises three processing units: (1) dismantling/board preparation; (2) pallet assembly/repair; and (3) painting/stamping. In addition, supporting processes such as utilities (office building, lighting, heating and cooling), dust collection and internal transportation with trucks and forklifts were accounted for in the repair/remanufacturing stage. Heat treatment is an optional process and was accounted for in the analysis, with about 11% of the repaired/remanufactured pallets heat treated. Coproducts generated at repair/remanufacturing facilities are typically beneficially used (e.g. mulch, animal bedding, wood fuel), but this study used the cut-off (recycled content) approach in line with the attributional LCA approach and did not account for potential benefits and burdens for coproducts.[17,18]

Using the attributional LCA approach, this study was performed in accordance with the ISO 14040[11] and ISO 14044[12] LCA standards. The declared unit for the gate-to-gate analysis was defined as one repaired/remanufactured pallet output. In this study, the declared unit was used instead of the functional unit as the product LCA does not cover the full life cycle,[19] and it refers to the number of pallets for use as a reference unit description, in line with the Product Category Rule for wooden pallets.[20]This study did not consider wooden pallets of a specific design or dimension, because the dimensions of pallets from different manufacturers varied based on the specific needs of pallet-using industries and the wood species used.[21] Therefore, the standardized dimensions of wooden pallets in North America were specified to be 1016 × 1219 mm (40 × 48 in), as defined by ISO standards.[22]

Inventory analysis

Using a survey developed for repaired/remanufactured pallet facilities, primary (foreground) data were collected and used to develop the LCI. The LCI was developed using the weighted-average approach to represent the industry-average production in the United States.[23] Forty repair/remanufacturing facilities that are distributed across the United States provided data representing about 12%, comprising 37 950 000 total repaired and remanufactured pallets producted in 2018. A majority of the data provided were from large-scale repair/remanufacturing companies. Some of the data were provided in an aggregated form where the data were collected from multiple sites of one company.

Table 1 represents the weighted-average inputs and outputs per one repaired/remanufactured pallet output. Repair/remanufacturing facilities use both softwood (SW) (72%) and hardwood (HW) (28%) lumber based on the 2018 data collected. About 90% of the lumber received for repair use was pre-cut (i.e. ready for use). The data collected from the repair/remanufacturing facilities showed that in 2018 about 90.1% of the recovered pallets on an oven-dried mass basis ended up as repaired/remanufactured pallets. Specifically, on an oven-dried mass basis, about 12% of the recovered pallets were reused without repair, about 31% were dismantled, about 53% were repaired and the remaining 4% were repurposed (ground into mulch, animal bedding, fuel). In addition to these repurposed pallets, parts of dismantled pallets were also repurposed

Table 1. Gate-to-gate process inputs and outputs based on weighted-average data from pallet repair/remanufacturing facilities per one repaired/remanufactured pallet output, mass allocation.

		Unit	Weighted average	Allocation
Products and coproducts	Pallet	Number	1	90.1%
	Sawdust	OD kg/pallet	2.67×10^{-2}	0.0%
	Hogged material (wood fuel)	OD kg/ pallet	4.98×10^{-1}	0.5%
	Wood chips (mulch)	OD kg/ pallet	5.62	9.3%
	Scrap wood (animal bedding)	OD kg/ pallet	6.11×10^{-2}	0.1%
Materials and fuels	Hardwood lumber	OD kg/pallet	2.31×10^{-1}	—
	Softwood lumber	OD kg/pallet	8.30×10^{-2}	—
	Natural gas	L/pallet	9.94	—
	Diesel	L/pallet	9.30×10^{-5}	—
	Propane	L/pallet	5.12×10^{-3}	—
	Diesel—forklift and trucks	L/pallet	2.40×10^{-4}	—
	Propane—forklifts	L/pallet	2.62×10^{-2}	—
	Truck transportation—lumber	t km/pallet	1.26×10^{-2}	—
	Transportation—pallet recovery	t km/pallet	1.21	—
	Staples	kg/pallet	2.54×10^{-5}	—
	Nails	kg/pallet	2.87×10^{-2}	—
	Paint	kg/pallet	1.66×10^{-4}	—
	Lubricating fluid	kg/pallet	1.11×10^{-3}	—
Electricity/heat	Electricity	kW h/pallet	1.42×10^{-1}	—
Waste	Steel scrap	g/pallet	1.77E $\times 10^{1}$	—
	Plastic wrap	g/pallet	2.59×10^{-1}	—
	Cardboard packaging	g/pallet	1.06×10^{1}	—
	Lubricants	g/pallet	3.69×10^{-1}	—

OD, Oven-dried.

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Table 2. Secondary data sources used in modeling the repaired/remanufactured pallet supply chain.

Raw material supply	Hardwood lumber	CORRIM datasets: sawn lumber, hardwood, green, rough, NE/NC USA, U
	Softwood lumber	CORRIM datasets: sawn lumber, softwood, rough, kiln dried, at kiln, m^3/SE_US
Raw material transportation	Trucking	DATASMART (US EI 2.2): transport, combination truck, diesel powered NREL/US U
Product manufacturing	Electricity	Ecoinvent 3.5: electricity, low voltage {US} | market group for | cut-off, U
	Natural gas	DATASMART (US EI 2.2): natural gas, combusted in industrial boiler NREL/RNA U
	Diesel	DATASMART (US EI 2.2): diesel, combusted in industrial equipment NREL/US U
	Liquid propane	DATASMART (US EI 2.2): liquefied petroleum gas, combusted in industrial boiler NREL/US U
	Fasteners (nails, staples, bolts, screws)	World steel association data
	Paint	DATASMART (US EI 2.2): alkyd paint, white, 60% in solvent, at plant/US-US-EI U
	Lubricating oil, grease	DATASMART (US EI 2.2): lubricating oil, at plant/US-US-EI U
	Waste landfilling	Ecoinvent 3.5: process-specific burden, sanitary landfill {RoW} | processing | cut-off, U

CORRIM, Consortium for Research on Renewable Industrial Materials.

into other products for a total of 9.9% of the incoming mass of recovered pallets. Of this 9.9%, 47% was sold as wood fuel, 52% was sold as mulch and a minor portion, about 1%, was sold as animal bedding. Most fasteners used in the facilities surveyed were nails, with smaller amounts of staples being reported. Natural gas was the major fuel consumed, which was mainly used for heat treatment and in utilities. It was followed by propane, which was reported to be used for heat treatment. Trucks and forklifts were used for the internal (onsite) transportation of pallets, where diesel and propane were consumed. Waste generated at repaired/remanufactured pallet facilities comprised steel scrap, plastic wrap, cardboard packaging and lubricants. The steel scrap generated was reported to be ~99% recycled. The weighted-average transportation distance (retailer to repair/remanufacture facility) for the recovered pallets was about 65 km.

At the repair/remanufacturing stage, wood coproducts are generated; therefore, allocation is required to separate the environmental burdens of pallet products from those of coproducts. In this study, the allocation was done on a mass basis while modeling the LCA and no cut-offs were used in the analysis. There is more discussion on allocation later on in this section. For the product systems under investigation, no consideration was given to the environmental impact resulting from infrastructure and equipment maintenance.

The primary data generated from the surveys was complemented by secondary (background) data available from databases and the literature (Table 2). The two major databases used for this study were ecoinvent v3.5[24] and DATASMART (US EI 2.2).[25] The data used for the SW and HW products used in pallet repair/remanufacturing were representative of US production and developed by the Consortium for Research on Renewable Industrial Materials (CORRIM).[26–28] Cradle-to-gate LCI data provided by the World Steel Association for 1 kg of steel wire rod was used to model the fastener production. It is assumed that diesel trucks are used for raw material transportation, including both transportation of virgin lumber and transportation of recovered pallets to the repair/remanufacturing facility. These data were modeled in SimaPro LCA software.

Life cycle impact assessment

For the environmental impact assessment, SimaPro version 9.1 software was used for LCIA in conjunction with the TRACI 2.1 impact assessment method and background processes databases.[29] The LCIA results were found using two different methods embedded in SimaPro. The first method, the TRACI 2.1,[30] reported the results on six impact categories: global warming (GW (kg CO_2 eq)), acidification (kg SO_2eq), eutrophication (kg N eq), ozone depletion (kg chlorofluorocarbons, kg CFC-11 eq), photochemical smog (kg NO_x eq) and fossil fuel depletion (MJ surplus). The second method, the Cumulative Energy Demand (CED) v1.00, published by ecoinvent,[31] quantified the primary energy consumption based on lower heating values.

Industry-level and individual facility-level mass balances were performed to verify the data quality. The repair/remanufacturing facilities receive and produce a wide variety of pallets in a variety of sizes and tracking the pallets' specifications is a complex task for which data were not available. Therefore, it was not possible to generate a mass balance based on specific mass data for each type of pallet received and produced. Pallet mass input and output were calculated based on the number of pallet input and output data provided by the facilities assuming that the mass of the pallet stays the same, 16.58 OD kg.[21] The uncertainty here results from the pallets being produced in a variety of sizes, which would result in different pallet mass input and output. Our current approach conservatively results in about a 90% allocation of the impact to the repaired/remanufactured pallet output. Since this assumption causes uncertainty in the LCIA results, a sensitivity analysis for allocation was conducted by assuming that 25% less impact is being allocated to the pallet product, which makes around 68% of the impact being allocated to the main product. Other allocation methods, i.e. economic and energy allocation, were also considered for sensitivity analysis. Economic allocation was not conducted owing to a lack of economic data and high variability of the price of a repaired/remanufactured pallet. Pricing highly depends on the regional market in which it is sold and its grade. Unlike lumber production, forced (kiln) drying is not performed in repaired/remanufactured wood pallet production; therefore, mass and energy allocation would have resulted in the same allocation ratio.

Sensitivity analysis

A sensitivity analysis was performed to further guide the impact assessment analysis and provide information on the relationship between the supply chain inputs and resulting environmental impacts. This study quantified the effect of variations in selected input parameters on the resulting environmental impacts. In this study, a sensitivity analysis was performed by evaluating the impacts of variations of lumber input, internal transportation, fastener use, electricity use and recovered pallet transportation distance on the overall GW impact. The parameter sensitivity was tested *via* its contribution to the GW impact for 25% variation in the selected input parameters.

Results

Life cycle impact assessment

The LCIA results for the six impact categories evaluated in this study are presented in Table 3. In addition, the contribution of different life cycle stages to the environmental impacts is presented in Fig. 2. The percentage contributions of the three life-cycle stages revealed the repair/remanufacturing stage to be the dominant contributor to most impact categories. Individual impact categories were also investigated in detail.

The ozone depletion potential of pallet repair/remanufacturing was estimated to be 9.51×10^{-9} kg CFC-11 eq/FU (Table 3). Ozone depletion is mainly caused by ultraviolet-B radiation to the surface of the Earth.[31] The use of electricity and lubricating oil during the manufacturing stage was the main contributor to the ozone depletion potential of pallet repair/remanufacturing (Fig. 2).

Gate-to-gate GW impact was estimated to be ~0.36 kg CO_2 eq/FU (Table 3). At the repair/remanufacturing stage, the electricity consumption used in the dismantle/board preparation and assembly/nailing unit processes was responsible for 38% of the repair/remanufacturing stage and 25% of the overall GW impact, respectively. The rest of the GW impact at the repair/remanufacturing stage mainly originated from the nails used (25%) and forklifts used in internal transportation (21%). The high contribution of raw material transportation, including transportation of recovered pallets and lumber, to the smog impact category was predominantly due to the recovered pallet transportation.

Smog generation of pallet repair/remanufacturing was estimated to be 2.97×10^{-2} kg O_3eq/FU (Table 3), which was mainly due to the transportation of raw material, and the use of liquified petroleum gas and electricity during the manufacturing stage (Fig. 2). The use of electricity during the manufacturing stage and the transportation of raw materials were also the main contributors to acidification, eutrophication and fossil fuel depletion potentials (Fig. 2).

The analysis of primary energy use for one repaired/remanufactured pallet output was performed using the CED method and the results are presented in Table 4. The total primary energy use was estimated to be 5.15 MJ/declared unit. Most of the primary energy use, i.e. 82%, came from non-renewable fossil sources followed by nuclear sources. The repair/remanufacturing stage (62% contribution) was the major reason for the high fossil resource use followed by raw material transportation (31% contribution). Nuclear resource use came from the electricity used in the repair/

Table 3. Gate-to-gate environmental impact of pallet repair/remanufacturing (declared unit: one repaired/remanufactured pallet output), mass allocation.

Impact category	Unit	Total
Ozone depletion	kg CFC-11 eq	9.51×10^{-9}
Global warming	kg CO_2 eq	3.55×10^{-1}
Smog	kg O_3 eq	2.97×10^{-2}
Acidification	kg SO_2eq	1.37×10^{-3}
Eutrophication	kg N eq	1.43×10^{-4}
Fossil fuel depletion	MJ surplus	5.00×10^{-1}

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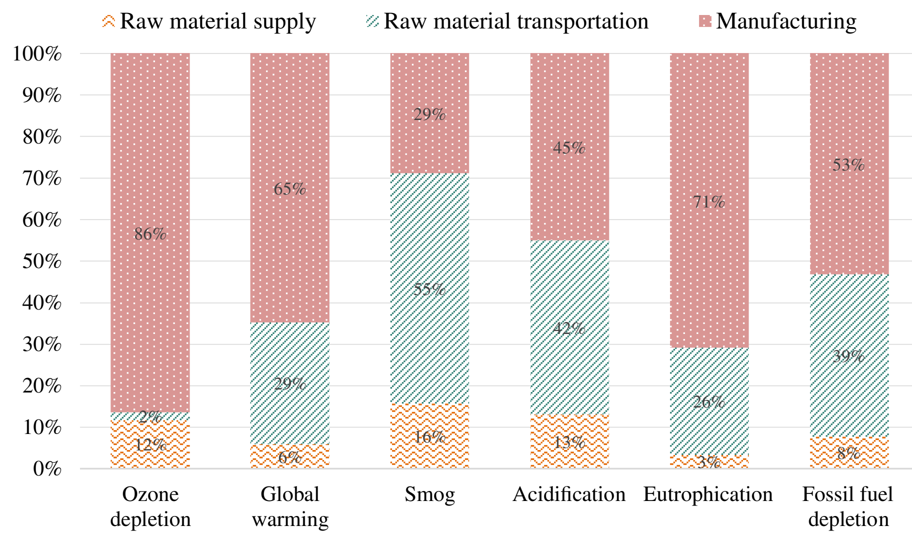

Figure 2. Contribution of the life-cycle stages of pallet repair and remanufacturing to the resulting environmental impact.

Table 4. Gate-to-gate primary energy use for pallet repair/remanufacturing (declared unit: one repaired/remanufactured pallet output), mass allocation.

Primary energy category	Total (MJ/declared unit)	Raw material supply (MJ/declared unit)	Raw material transportation (MJ/declared unit)	Repair/ remanufacturing (MJ/declared unit)
Non-renewable, fossil	4.15×10^{0}	2.60×10^{-1}	1.30×10^{0}	2.59×10^{0}
Non-renewable, nuclear	5.02×10^{-1}	7.72×10^{-2}	1.88×10^{-2}	4.06×10^{-1}
Non-renewable, biomass	1.12×10^{-6}	3.21×10^{-7}	6.02×10^{-10}	7.95×10^{-7}
Renewable, biomass	3.51×10^{-1}	3.40×10^{-1}	4.72×10^{-4}	1.01×10^{-2}
Renewable, wind, solar, geothermal	3.49×10^{-2}	1.65×10^{-3}	6.55×10^{-4}	3.26×10^{-2}
Renewable, water (hydro)	5.20×10^{-2}	9.38×10^{-3}	1.66×10^{-3}	4.09×10^{-2}
Total	5.09×10^{0}	6.88×10^{-1}	1.32×10^{0}	3.08×10^{0}

remanufacturing stage. The electricity consumption, nails used and forklifts used in internal transportation also had a notable influence on fossil energy use with ~23, ~15 and ~11% contributions, respectively. Similarly, Park *et al.*[13] reported that the electricity and nails used were the key inputs influencing the greenhouse gas (GHG) emissions. The renewable biomass energy use was mainly (~97%) due to the use of wood fuel at the raw material supply stage for forced drying during lumber manufacturing, which is typical.[32–34]

Sensitivity analysis

The influence of variations in the selected parameters on the GW impact per one repaired/remanufactured pallet output is presented in Fig. 3. The transportation of the recovered pallets to repair/remanufacturing facilities had the highest influence on the total GW impact. This indicates that reducing the transportation of the recovered pallets by 25% would reduce the overall GW impact by 7.2% (Fig. 3). Electricity consumption was also a main parameter affecting the GW impact of the repaired/remanufactured pallet, so that reducing electricity use by 25% would reduce the overall GW impact by 6.2% (Fig. 3). Fasteners used in the repair/remanufacturing stage and internal transportation fuel use were somewhat less important parameters affecting the GW impact of repair/remanufacturing pallets. Because the amount of lumber used as raw material was small, it did not have a notable influence on the resulting impact.

The sensitivity of the GW impact to the allocation was investigated for the case where 25% less impact is allocated to the pallet product. The allocation sensitivity showed that the repaired/remanufactured pallet case is very sensitive to the allocation used, where a 20% decrease in GW impact, from 0.355 to 0.284 kg CO_2 eq, was observed.

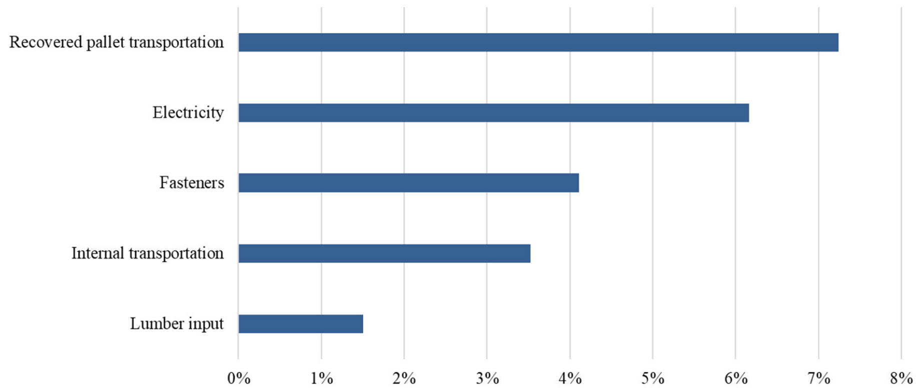

Figure 3. Sensitivity of parameters on global warming impact of pallet repair/remanufacturing (declared unit: one repaired/remanufactured pallet), mass allocation.

Discussion

This study provides a representative industry-average repaired/remanufactured pallet LCI developed to show the life cycle environmental impacts and primary energy use for a more accurate assessment of the wood pallet supply chain. The gate-to-gate GW impact for the selected declared unit (one repaired/remanufactured pallet output) was estimated to be 0.355 kg CO_2 eq. Deviatkin *et al.*[35] reported that the GW impact values vary significantly per pallet produced, because it depends on many different factors, e.g. system boundaries, pallet type and design, life cycle stages included, etc. However, the minimum GW impact value reported per new pallet manufactured was about 2.2 kg CO_2 eq without accounting for potential environmental benefits, which is substantially higher than the value reported here for producing one repaired/remanufactured pallet. Park *et al.*[13] reported gate-to-gate GHG emissions from the pallet repair process of about 0.14 g CO_2 eq. The lower impact reported in that study can result from the transportation of raw materials, which was not accounted for by Park *et al.*[13]

The contribution analysis identified the most influencial parameters for the environmental impact categories of the repair/remanufacturing pallets. In addition, sensitivity analysis identified the sensitive parameters which help mitigate potential sources of uncertainties. Electricity demand at the repair/remanufacturing stage was responsible for the high impact (16% of the total GW impact), resulting from the electricity grid being predominantly fossil-based. The use of wood waste generated at the facility at cogeneration systems to supply biomass-sourced energy could help mitigate GW impact owing to fossil-based energy use. The transportation life cycle stage also made a notable contribution to the overall environmental impact, with a 29% contribution to the overall GW impact. This was mainly due to the pallet recovery transportation. Transportation of recovered pallets and electricity use were also identified as the most sensitive parameters affecting the GW impact of pallet repair/remanufacturing. The transportation-associated emissions are a function of the transportation mode (e.g. diesel truck, rail) and distance, as well as the type of fuel and engine with the corresponding emission factor.[14] In this study, the recovered wooden pallets were mostly transported using diesel trucks for a weighted average of 65 km. However, there was a wide range of transportation distances (25–100 km) between the investigated facilities, which causes uncertainty in the results.[21] Reducing the transportation distance by increasing the number of facilities, and also using more energy-efficient transportation modes (e.g. rail), would reduce the emissions associated with transportation. Transportation was identified to be an important stage for GHG emissions by Carrano *et al.*[14] with about a 41% contribution to refurbishing-stage emissions for stringer pallets and 55% for block pallets. Nails used at the repair/remanufacturing stage were also identified to be a key component with a high environmental impact, which was in line with the findings of the previous study.[13] Just like most wood products, the high contribution from electricity used was the major contributor to the resulting impacts.[32,33,36] The environmental impact resulting from the raw material supply stage was not significant as compared with new pallet manufacturing.[19] This was mainly from the low amounts of virgin (new) lumber consumed during the manufacturing stage. For pallet repair and remanufacturing, the wood boards used are mainly supplied from dismantled pallets. Given the scale of data collected and the number of facilities included in the analysis, it was not possible to collect process-level data. Yet it would be valuable to generate a gate-to-gate life cycle inventory. This would allow the evaluation of impacts resulting from different unit processes and environmental hotspots within the repair/remanufacturing facility.

The importance of the repair/remanufacturing stage has been shown in previous studies because of its potential to decrease the overall environmental impact of the wood pallet sector by extending the service life of individual pallets.[14,21] Alanya-Rosenbaum *et al.*[21] showed that the contribution of the repair/remanufacturing stage to the gate-to-grave GW impact of the wood pallet was low, about 5%, compared with other life cycle stages. The low environmental impacts of repaired/remanufactured pallets and their effect on the pallet service life make them a key component when considering the overall environmental contributions of the wood pallet supply chain.

Typically, wood pallets can be recovered and repaired multiple times throughout their life cycle. This study shows that repaired/remanufactured pallets have a low environmental impact profile compared with new pallet manufacture as reported in previous studies.[13,14,21] Because repair/remanufacturing has a comparatively low impact and can extent the reference service life of a pallet, multiple repairs and further mitigation of the environmental impacts of the repair stage have a high potential to reduce the overall life cycle environmental impacts of a wood pallet. It is worth mentioning that the quality of repaired/remanufactured pallets is an important factor that needs to be considered for the LCA. Pallet components degrade as they are used and their service life goes down over time. However, repair increases the reference service life, which has an effect on the life cycle environmental impact of the pallet.

Conclusions

This study developed a gate-to-gate industry-average LCI based on primary data collected from US repair/remanufacturing facilities. In addition to developing unique LCI data, an LCIA was conducted to fully assess the comprehensive life cycle environmental impacts of a repaired/remanufactured pallet. The authors identified the sensitivity of LCIA impact scores to key parameters used in the supply chain analysis. The LCI developed for high-quality assessment of future wood pallet LCAs accounting for the repair/remanufacturing stage and the results presented here identify potential improvement areas to mitigate overall environmental impacts.

The repair/remanufacturing stage drives much of the impact on the environment with a high contribution from the electricity used followed by nail input and the fuel used by forklifts. Fossil fuel use was the major contributor to overall primary energy use. Reducing fossil fuel usage is the highest priority for reducing overall impacts. Lowering the effect of nails and their production supply chain is a key factor for improving overall performance. The total GW impact was highly sensitive to the transport distance of the recovered pallet. Pallet recovery/transportation to the repair/remanufacturing facilities was identified as another key factor affecting most impact categories. Given that there is an increasing repaired/remanufactured pallet to new wood pallet production ratio, recovered wood pallet transportation ought to go down as more companies enter the market.

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