Characterizing the Carbon Footprint of Wood Pallet Logistics

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Abstract

Pallets are one of the basic building blocks of supply chains. Pallets are the most common unit-load platform used across the world and allow for efficient and seamless handling, storage, and transportation of goods. Every year, 500 million new pallets are manufactured and become part of the large pool (roughly 2 billion) of pallets that are in circulation in the United States. Wood remains the most common pallet material, accounting for more than 90 percent of the inventory and applications worldwide. As companies strive to become more sustainable, a thorough understanding of the environmental impacts of every aspect of their logistics operations becomes critical. Among the many factors affecting the life cycle of wood pallets are the pallet structural design, logistics management approach, and service environment conditions. This work is the result of a comprehensive 2-year study on the operations and practices that take place during a wood pallet life cycle. In this article, a prescribed approach for estimating the carbon footprint, or greenhouse gas emissions, that arise across all phases of a pallet life cycle, is presented. In addition, the impact of contributing materials, processes, and activities in each phase is quantified. The findings presented in this article provide a foundation to guide strategies on pallet design and returnable container network and policy design.

Supply chains are becoming more and more complex. This is due to many factors, including the expansion of global markets and product storage-keeping units, an increased variety of shipping and distribution modes, and rising expectations from customers, particularly with respect to service levels and delivery times. At the same time, companies are striving to make their supply chains more efficient and more sustainable. One way to do so is to evaluate every aspect of their shipping and distribution operations to understand their environmental impact. Pallets are the most common unit-load platform for handling and storing goods and are a critical component of these operations. Because large numbers of pallets are typically used when producing and distributing goods, the seemingly small environmental impact associated with the use of a single pallet is greatly magnified by the scale of the operations.

The Department of Transportation (Bureau of Transportation Statistics 2009) estimates that transportation represents roughly 10 percent of the US gross domestic product, or approximately $1.4 trillion. In 2006, some 8.8 million trucks traveled approximately 423 billion km. In 2010, transportation, in its many forms, generated 1,857 million metric tons of carbon dioxide equivalent (CO_2 eq) emissions, accounting for 27 percent of total US greenhouse gas (GHG) emissions (US Environmental Protection Agency [US EPA] 2014). Also, in 2010, freight transportation generated 525 million metric tons of CO_2 eq emissions, over 28 percent of the transportation emissions generated that year (Federal Highway Administration [FHWA] 2014). So for 2010, freight transportation generated about 7.5 percent of all US GHG emissions. Total GHG emissions from the freight sector have grown by 47 percent since 1990 (FHWA 2014). It is estimated that 80 percent of US trade is carried on pallets (Raballand and Aldaz-Carroll 2007). Every year, approximately 450 to 500 million new pallets are manufactured and become part of the large pool (roughly 2 billion) of pallets that are in circulation in the United States (Buehlmann et al. 2009). Solid wood remains the most common pallet material, accounting for 90 to 95 percent of the inventory and applications worldwide (Buehlmann et al. 2009, Mead 2010). Traditionally, the

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pallet industry has been the single-largest destination of hardwood lumber in the United States, consuming about 3.8 $\times 10^{12}$ board feet (fbm), or about 33 to 50 percent of all hardwood lumber (McKeever and Dickerhoof 1980, Buehlmann et al. 2009). Many of these pallets are used only a few times and end up meeting a variety of end-of-life scenarios (e.g., landfill, municipal incineration, or downcycling), while others are refurbished and reused many times. It is estimated that pallets are responsible for 2 to 3 percent of all waste landfilled in the United States (Buehlmann et al. 2009). As companies set goals to become more sustainable, a thorough understanding of the environmental impacts of their pallet operations becomes critical.

The manner in which pallets are managed throughout their life cycle can produce a notable difference on the environmental impacts as well as on the costs that arise from pallet operations (Bilbao et al. 2011). In the United States, the past two decades have seen an increase in the adoption of outsourced pallet logistics. This rental model, sometimes called leased pallet pooling, allows companies to focus on their core business while outsourcing their needs and concerns for handling, sorting, refurbishing, treating, and eventually disposing their pallets to a third-party company.

The ability to control the return logistics of the pallets and thus the ensuing refurbishing and end-of-life destination of the pallets allows pooling service companies to provide logistics arrangements that are attractive to those companies seeking to manage their carbon footprint. However, the complexities of today's supply chains and the breadth of environmental impacts pose interesting challenges to those seeking to engage in sustainable practices. This article aims to (1) provide a thorough analysis of the activities and their corresponding GHG impacts in each phase in the pallet life cycle, (2) provide an approach to calculate the GHG emissions for each phase and under specific assumptions, and (3) provide a list of potential areas for improvement in each phase. It is hoped that this article will help increase the understanding of the impacts of decisions at each life-cycle phase for pallets and, by extension, returnable containers and other forms of packaging. This, in turn, will support decision making when choosing pallet designs, sourcing, treatments, and take-back logistics and recycling practices.

Background

Figure 1 depicts the general flow of wood pallets throughout their life cycle. In the broadest sense, a pallet life cycle includes the following phases: raw material

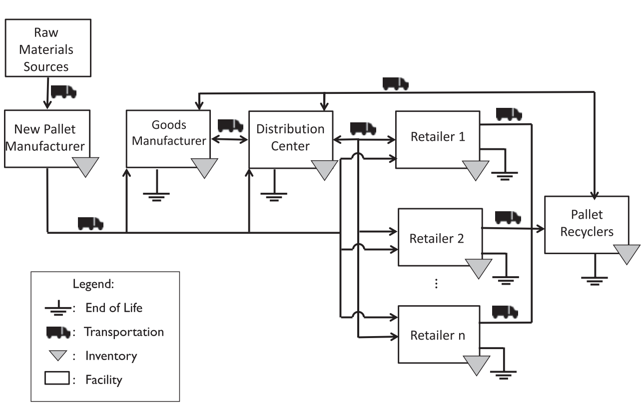


Figure 1.—General life-cycle flow of wood pallets.

extraction and premanufacturing, manufacturing, transportation and use, refurbishing, and end-of-life disposal. The processes and activities included in each phase are described in this section.

Raw material extraction and premanufacturing phase

The raw material extraction and premanufacturing phase includes sourcing (harvesting and mining) of the raw materials as well as the primary manufacturing to turn the mined ores and wood logs into steel and lumber boards at the mills. Trees are felled, transported from the forests to the mills, and turned into wood products. The various purposes and pallet management strategies may require pallet designs that include different choices and quantities of materials. For example, a single-use (expendable) pallet will likely be designed as a simple, lighter structure (e.g., single face, nonreversible) that can withstand the conditions on a flatbed distribution leg but lacks the design reinforcements and additional fasteners needed to withstand multiple trips. The materials of choice for these disposable pallets might include greater proportions of inexpensive lumber (e.g., regionally available softwoods), engineered woods (oriented strand board or plywood), structured paper (corrugated fiberboard), or a mixed product (lumber-reinforced cardboard). On the other hand, reusable pallets performing within closed-loop systems are typically designed to be more robust, with higher deck coverage and hardwood leading-edge boards. These increase the consequent weight and durability of the platform but also increase the quantity and diversity of the materials. Approximately 90 percent of the pallets that are manufactured are made out of solid wood, with mixed eastern oaks species (*Quercus* spp.) being the dominant hardwood (22.4%) and southern yellow pine species (*Pinus* spp.) being the dominant softwood (7.1%; Bush and Araman 2008). It has been reported (McKeever et al. 1986) that the average pallet contains 12.7 fbm of wood. However, a pallet may well contain anywhere between 8 and 22 fbm of wood, depending on design and structural features. The average expendable (single-use) pallet contains 10.1 fbm of wood (73% of which is hardwood), while a reusable (multiple-use) pallet uses approximately 50 percent more wood for an average of 15.4 fbm (87% of which is hardwood). Table 1 shows the average wood content of pallets manufactured in the United States.

Typically, when it comes to fasteners, steel nails with formed grooves for increased withdrawal resistance are used for new pallet manufacturing. Sometimes, during refurbishing operations, metal connector plates are used, but they are rarely used for new pallets. While the type and number of nails utilized in pallet production can vary depending on the pallet design specifications, a 48 by 40-inch nonreversible stringer pallet was found to use an average of 84 helically threaded nails of identical length (3.12×10^{-3} kg per nail). Similarly, a newly manufactured block pallet was found to contain an average of 102 annularly threaded nails of two different lengths (1.70×10^{-3} kg per short nail and 4.46×10^{-3} kg per long nail). An accurate impact assessment accounts for all primary processing needed to produce steel stock from raw materials, including mining and extraction of the iron ores, smelting processes, the production of steel wire, and the transportation needed for each step. It should also include the manufacturing processes to produce the nails: primary forming of the head and point, secondary

Table 1.—Average wood content of pallets manufactured in the United States (McKeever et al. 1986).

Pallet type/wood product	Average wood content (fbm)
Reusable (multiple use)	
Hardwood lumber	13.3
Oak	7.4
Other hardwoods	5.9
Softwood lumber	1.8
Plywood	0.2
Total	15.3
Expendable (single use)	
Hardwood lumber	7.4
Oak	3.1
Other hardwoods	4.3
Softwood lumber	2.7
Plywood	0.0
Total	10.1

forming of the grooves in the shank, cleaning in rotating caustic soda barrels, finishing, and surface treatment. Most nails used for pallets are galvanized for corrosion resistance via hot-dip tanks of molten zinc; thus, the energy requirement of this process must also be included. Finally, transportation from the fastener manufacturer to the final point of use should be included.

Manufacturing phase

The manufacturing phase includes the design, fabrication, and assembly activities of stringer and block pallets. This comprises the emissions associated with the transportation of lumber from the mills to the pallet manufacturing facilities, the assembly operations, the kiln drying, and phytosanitary measures (i.e., heat treatment). The pallet manufacturers located in the geographical scope of this study fabricated their pallets by following the same general steps: component dimensioning (stringer, leadboard, and block), kiln drying and mold dipping, pallet assembly (including branding), and sterilization (mainly by heat treatment). With respect to lumber-drying activities, the American Lumber Standard Committee (2002) in its wood packaging material policy recommends that pallets be seasoned in a closed chamber to reduce the moisture content to a recommended 19 percent or less equilibrium moisture content (EMC). The drying operation can be performed in kilns or by air-drying at the component level (before the boards are assembled) or after the pallet has been assembled. The impact of GHG emissions derived from natural air-drying is minimal and considered negligible. In the case where kilns are used to season the lumber, an estimate of the kiln energy consumption, kiln cycle, number of pallets per cycle, and initial and final EMC are required to estimate the emissions.

Transportation and use phase

The use phase of a pallet takes place during transportation of the goods that it carries across the various echelons in the supply chain (e.g., from product manufacturing plant to the distribution center and from there to the retailer). While this phase includes only transportation segments where pallets are loaded with products, the emissions impacts are limited to those caused by the tare weight of the pallet on those loaded segments. The tare weight of the pallet is a function of many factors, primarily the pallet design, the volume and density of the materials (i.e., wood species mix and steel), and the moisture content of the wood at the time of transportation. The moisture content of the wood can add significant weight to the pallet, thus increasing its emission impacts for the transportation and use phase. Under certain conditions, a pallet manufactured with green lumber can lose up to 45 percent of its weight through air-drying. It is not uncommon for pallets to achieve 10 to 12 percent EMC by the end of their useful life (White and McLeod 1989). The emissions associated with the transportation mode are a function of the type of fuel and engine with its corresponding fuel oxidation factor. All these factors need to be accounted for when attempting to inventory the impacts of this phase.

Refurbishing phase

The refurbishing phase includes the repair and replacement of pallet components. With the exception of single-use expendable pallets, which are obviously not intended for refurbishing and multiple uses, most pallets in circulation experience some level of refurbishing throughout their life cycle. Many of them are refurbished multiple times. It was estimated that the pallet industry received an estimated 460.7 million used pallets (e.g., recovered, repaired, and/or remanufactured) for recycling in 2006 (Bush and Araman 2009). It has been reported that approximately 87 percent of the wood contained in pallets received for recycling is used again in a pallet (Bush et al. 1997). Also, it is estimated that one in four pallets in circulation is a recovered/repaired pallet (Araman et al. 1998). In this phase, all the emissions associated with the transportation from the end point in the supply chain to the refurbishing depots, the disassembly and refurbishing processes for blocks, stringers, lead, and deck boards, and the transportation impacts from repositioning the pallet back into use, are determined. This is, admittedly, the most difficult phase to characterize, as the number of refurbishing trips and the exact nature of the failure is dependent on many factors, including service environment conditions as well as characteristics of local reverse-logistics systems. The impacts of refurbishing materials in the form of added fasteners and metal plates must be included as well. However, added wood for replacing missing or severely damaged components of the pallet is typically sourced from other dismantled pallets. This was observed to be a widespread practice among pallet recyclers. Therefore, the emissions of replacement wood components are already accounted for. The complexity of the refurbishing process of pallets is dependent on the type and severity of damage and the type of fastener or plate being applied. Some of the larger-volume facilities and leased pallet-pooling operations divided the remanufacturing stream into ‘‘general repair’’ and ‘‘difficult repair.’’ About 8 percent of all pallets that needed repair fell into the category of ‘‘difficult repair,’’ while some 3 percent of all pallets were diverted to the complete teardown stream. The pallets requiring general repair were delivered to a station where typically one operator completed the entire operation. This might consist of a leadboard or block replacement, etc. At one facility, a general repair took an average of 100 seconds per pallet (36 pallets per h per station) and contained approximately 30 work elements (steps). The tooling typically available consisted of a pneumatic disc grinder, a pneumatic nail gun, several manual tools (specialty dismantling bars and hammers), and a rotary table (either turntable or ball table) with lifting capabilities for pallet overturn. The difficult repair presented a wide range of operations, materials, and supplies and consequently exhibited a large variability of process times. Depending on the severity of damage, this could represent the installation of metal connector plates, companion stringers, or full deck boards. Finally, some pallets are heat treated again after refurbishing for export compliance purposes.

End-of-life disposal phase

The end-of-life disposal phase includes disposition of the pallets at the end of their useful life. It is estimated that somewhere between 3×10^{12} and 4×10^{12} fbm of wood waste is generated from discarded pallets (Aruna et al. 1997), an increase from 1.24×10^{12} fbm in 1993 (Bush et al. 1997). A characterization of the municipal solid waste (MSW) by weight in the United States (US EPA 2011) estimates that wood packaging, mostly in the form of pallets, accounts for 10.0 million tons of wood (4% of total MSW generation), of which 6.16 million tons entered the landfill facilities (Araman et al. 1998). A survey of 103 pallet recyclers in North Carolina found that 20 percent of the pallets received were reused, 45 percent were refurbished, 19 percent were recycled, and 15 percent were ground (Buehlmann et al. 2009). The remainder, 1 percent, are presumed to be landfilled. The methods by which pallets are disposed of when they must be retired can result in very different environmental impacts. Four distinct end-of-life scenarios are typically considered: landfilling, mulching (for landscaping, livestock bedding, and poultry litter applications), incineration with energy recovery, and incineration without energy recovery. These typically occur when the pallet is damaged beyond repair and/or its components are too worn out or damaged to serve as donor lumber to other pallets. Also, a perfectly functional pallet, for a variety of reasons (e.g., lack of take-back logistics, lack of market for odd sizes), may not find its way back into the pallet pool, thus meeting a premature end of life.

Methods

The data collection for this study was conducted in facilities located in the northeastern and southeastern United States. Although the activities per se at the various locations (lumber mills, pallet depots, etc.) are essentially the same, regional differences in supply chain configurations, sourcing/delivery distances, and disposal practices might vary somewhat. Three types of 48 by 40-inch pallets were assessed for their impact: single-use expendable, reusable stringer, and reusable block pallets. The 48 by 40-inch pallets account for about 30 percent of all pallets manufactured in a given year (Clarke 2004).

This study relied on data acquired through direct observations and time studies performed at 12 facilities involved in the various aspects of pallet manufacturing, refurbishing, and disposal operations. These included lumber mills, pallet manufacturers, pallet recyclers, and pallet-pooling providers (both third-party-owned and third-party-managed pooling companies) located in the United States. During these visits, a complete documentation of their standard practices was conducted.

Specifically, the following information was gathered from direct observations on the plant floor and time studies: average time for new build per pallet type, average time for component repair and replacement by pallet component and severity, materials used in new build and refurbishing operations, and type of equipment (with capacities, power consumption, and fuel specifications). The following information was provided by the various companies participating in the study: average transportation distance for the lumber (from mills to pallet manufacturing facility), average transportation distance from pallet manufacturing facility to pallet user facilities, average transportation distance from pallet user facilities to refurbishing depots, and transportation modes (e.g., truck, rail) with capacities and fuel types.

The estimation of the GHG emissions impact for each phase involved calculation of carbon equivalent emissions by constructing custom processes using SimaPro life-cycle assessment (LCA) modeling software (PRé Consultants 2011). The estimation of the impact for each phase involved one or more of these processes. SimaPro extracted process inventory data from the EcoInvent database (Swiss Centre for Life Cycle Inventories 2009). The impact assessment method focused on the carbon footprint as measured in kilograms of CO_2 equivalents emitted for a 100-year time horizon (Intergovernmental Panel on Climate Change 2007) by each process or activity and summed within each LCA phase. The equivalency of emissions was calculated using the global warming potential ratios of the emission gases involved.

In addition, two global assumptions related to energy sources and their corresponding emissions were made throughout the study:

- The carbon equivalent emissions from transportation by mode were adapted from the EcoInvent database (Swiss Centre for Life Cycle Inventories 2009). The values used for sea freight, rail freight, and diesel truck transportation were 0.0107, 0.0497, and 0.1070 kg CO_2 eq/ton-km, respectively.
- Based on their percentages in the US grid (US Energy Information Administration 2011), the national weighted average conversion of carbon equivalent emissions by energy source was assumed to be 0.648 kg CO_2 eq/kWh.

Finally, the emissions associated with infrastructure and facility operations (e.g., internal material handling, lighting, heating, ventilating, and air-conditioning) were not included.

Results

Raw material extraction and premanufacturing phase

The sources of timber were observed to be located usually within a 480-km radius from the lumber mill. The timber included small-diameter (600 mm or less) logs that were intended for pallet manufacturing in its entirety or larger-diameter logs that were intended for production of higher-value products, such as furniture, and from which ''cants'' (i.e., boards not suitable for higher-value applications) were extracted. The average wood content in the pallets observed in this study were 10.0 fbm (48 by 40-in. single-use expendable), 13.5 fbm (48 by 40-in. reusable stringer), and 20.0 fbm (48 by 40-in. reusable block). With respect to the wood species used in the manufacturing of pallets, almost

Table 2.—Emissions from materials in a 48 by 40-inch pallet.

Material (unit)	Emissions (kg CO_2 eq/unit)	Quantity (units/pallet)		
		Expendable	Stringer	Block
Mixed hardwoods (fbm)	0.185	0	13.5	5
Mixed softwoods (fbm)	0.134	10	0	15
Annularly threaded long nail (count)	0.008	0	0	48
Annularly threaded short nail (count)	0.003	0	0	54
Helically threaded nails (count)	0.005	72	84	0
Total materials emissions (kg CO_2 eq/pallet)		1.73	2.95	3.47

any regionally available hardwoods and softwoods were used. Some studies suggest that a significant percentage of the wood destined for pallet manufacture (around 25% to 33%) is diverted to a waste stream. Moreover, it has been reported that 17 fbm was needed to fabricate a 12.7-fbm pallet (McKeever et al. 1986). However, the dominant practices observed among the manufacturers favored using the wood waste stream for other purposes (e.g., odd-size pallets, small crates, high-quality sawdust). Hence, this wood stream must be accounted for as a by-product and not as a waste. As such, the implications on the carbon footprint are that, strictly, the wood mass that becomes part of the pallet is to be included in the calculations.

To calculate the GHG emissions associated with the production of lumber, it is necessary to gather the energy inputs required to source and transport the logs to the mills and to process them into standard-size boards. Modeling the primary processes for sawn timber with the conditions and activities mentioned above, resulted in the following emissions: 56.5 kg CO_2 eq/m^3 for sawn hardwoods air-dried to 20 percent EMC, 78.50 kg CO_2 eq/m^3 for sawn hardwoods kiln dried to 10 percent EMC, 56.90 kg CO_2 eq/m^3 for sawn softwood air-dried to 20 percent EMC, and 73.40 kg CO_2 eq/m^3 for sawn softwood kiln dried to 10 percent EMC (PRé Consultants 2011).

The other material with significant presence in pallets is ferrous metals for fasteners. Modeling the primary processes for low-alloy steel in SimaPro yields 1.72 kg CO_2 eq/kg. Table 2 shows the emissions derived from the materials based on the SimaPro LCA model and for the three different type of pallets considered.

The results from the materials phase clearly show the increase in GHG emissions as a direct consequence of the amounts of materials that compose a pallet. Reusable block pallets contain the highest amount of lumber and nails and therefore result in a higher CO_2 eq emission than that of the other types. Single-use expendable pallets contain the least amount of materials, limiting their life expectancy and thus resulting in the lowest GHG impact in the materials phase. In general, wood accounts for the majority of the impact (an average of 82% across all pallet types) of the total CO_2-eq emissions, while steel is responsible for the remaining 18 percent.

Manufacturing phase

Once the boards and blocks are dimensioned, the pallet is assembled with specialty nails. The variation in assembly cycle times between types of pallets is not as significant as the difference due to the different levels of assembly process automation. For the type of pallets considered in this study, a fully manual assembly process (one operator) takes an average assembly time of approximately 2 min per pallet. A semiautomated pneumatic nailing machine with three parallel nail gun heads and automatic stringer feeder averaged 1.5 min per pallet. With this equipment, the operator sets the deck boards on the stringers before the nail gun heads travel over the boards. A fully automated pallet assembly machine performed average cycle times in the range of 0.5 to 1.0 min per pallet. With respect to energy requirement, as an example, the most common equipment used to assemble stringer pallets consisted of a three-head electric nailing machine (5 horsepower, 230-volt AC from the grid, 0.9629 m^3/min).

The energy requirements to assemble one pallet of each type with its associated GHG emissions are expendable pallet (0.124 kWh per pallet; 0.081 kg CO_2 eq/kWh), stringer pallet (0.093 kWh per pallet; 0.060 kg CO_2 eq/kWh), and block pallet (0.062 kWh per pallet; 0.040 kg CO_2 eq/kWh). These results take into account the equipment capacity (as determined by the pallet type) and the average conversion for grid energy mix in the United States. The efficiency of the higher-volume processes used in the fabrication of block pallets translates into a shorter cycle time and thereby results in a lower emissions impact than the alternative options.

With respect to phytosanitation by heat treatment, there are three approaches: kiln drying, heat-enabled chemical pressure impregnation, and microwave treatment (International Plant Protection Convention 2009). In this study, 100 percent of the manufacturers visited conformed to phytosanitary measures by heat treatment in modified kiln-dry chambers. The heat treatment cycles lasted an average process time of 1.5 hours and were performed in kilns that were powered by natural gas. The average energy consumption of kilns with a maximum capacity of 600 pallets was 850,000 BTU/h. Based on SimaPro modeling, the GHG emissions per pallet treated are calculated as 0.153 kg CO_2 eq per pallet regardless of the type of pallet being treated. It should be noted that this impact is determined by the capacity of the chambers, so it is identical for all types of pallets and should be added to the emissions associated to the assembly process.

Transportation and use phase

These two phases are combined because the use phase of a pallet occurs when transporting the goods that it carries. The pallets described in Table 2 weigh 13.79 kg (single-use expendable), 29.73 kg (reusable stringer), and 31.58 kg (reusable block). Owing to the uncertainty surrounding the life expectancy of a pallet as well as the conditions to which

Table 3.—Transportation emissions per pallet type and transportation mode.

Transportation mode	Emissions (kg CO_2 eq/pallet-km)		
	Expendable	Stringer	Block
Sea freight	1.48×10^{-4}	3.18×10^{-4}	3.38×10^{-4}
Rail freight	6.86×10^{-4}	1.48×10^{-3}	1.57×10^{-3}
Diesel truck (32 ton)	1.48×10^{-3}	3.18×10^{-3}	3.38×10^{-3}

it is exposed during its life, it is convenient to assume that the weight at manufacture is maintained throughout the life of the pallet. This conservative assumption provides a worst-case scenario for emissions in this phase. The emission factor for each corresponding type of fuel is applied to the energy requirements per transportation mode and the weight of each type of pallet to obtain the emissions when moving a pallet over a distance of 1 km. Table 3 depicts transportation emissions per pallet type and transportation mode.

Refurbishing phase

For this phase, a characterization of the expected durability and the ensuing refurbishing cycles based on a series of assumptions is utilized. Estimating pallet durability for a pallet pool in an accurate way is very difficult and will be assumption laden. Most models used in software such as PDS (Pallet Design System) use inputs such as the type of handling and treatment, weight of loads, and EMC to predict the service life for a specific pallet design (National Wooden Pallet and Container Association 2011). This type of analysis is an average characterization and is not necessarily representative of the life of every pallet in the population, even if subjected to identical conditions. This large variability presents an enormous challenge when trying to characterize this phase for environmental impacts. White and Wallin (1987) studied 877 stringer pallets (48 by 40 in.) in a variety of service environments for over 3 years. They found that pallet design and service environment conditions can cause a variation of more than 500 percent in actual durability with an average ranging between 58 and 298 damage-free handlings. Also, the nonstandard units of measure for pallet life expectancy and durability present a challenge. Life expectancy or durability can be measured in ''handlings'' (a single lifting, movement, and placement), a ''trip'' (consisting of four to six handlings), or ''cycles'' (a unit within an accelerated rough-handling test protocol developed by Virginia Tech (FasTrack 2008).

A longitudinal characterization of the refurbishing process that a given pallet experiences throughout its life is also difficult. A service life analysis from software such as PDS can provide some insight with respect to the frequency and type of refurbishing that an average pallet might undergo under specific conditions.

Table 4 shows the predicted service life (measured in FasTrack material handling cycles) and predicted breakdown pattern (measured in the total trips to the repair depot and the total number of components replaced or repaired throughout its useful life) for similar block and stringer pallets under a variety of service conditions and loads.

It should be noted that the information in Table 4 cannot be used to compare across type of pallet (block vs. stringer) since the structure, fasteners, and mix of wood species are not the same but rather across conditions for the same type of pallet.

The impact of the refurbishment processes for a wooden pallet throughout its life cycle is calculated by estimating the emissions associated with the materials that go into a repair or replacement operation (multiplied by the number of components repaired during its lifetime), the emissions associated with the operations of the tools and equipment utilized during one refurbishment operation (multiplied by the number of repair or replacement operations during its lifetime), and the emissions associated with the round trip to the repair depot (multiplied by the number of trips during its lifetime). Table 5 shows the GHG emissions associated with refurbishment of wooden block and stringer pallets under various loading and handling conditions.

It should be noted that these numbers represent the cumulative impact arising from refurbishment operations for the entire life of the pallet. Consequently, a pallet that lasts longer is potentially repaired many more times (with the corresponding impacts) than one that experiences a service environment leading to shorter life.

Finally, the individual contributions to the GHG emissions in the refurbishment phase for stringer pallets are materials (47%), transportation (41%), and equipment (12%). For the block pallets, the individual contributions are materials (28%), transportation (55%), and equipment (17%).

Table 4.—Predicted service life and breakdown pattern for average and extreme service duty conditions.[a]

Handling environment severity	Predicted service life units, no. of cycles (no. of trips) no. of components repaired					
	Light-duty loads (1,000 lb)		Medium-duty loads (2,000 lb)		Heavy-duty loads (3,000 lb)	
	Stringer	Block	Stringer	Block	Stringer	Block
Good handling and treatment	26 (6) 6[b]	30 (7) 7[c]			7 (4) 4	21 (12) 12
Average handling and treatment			9 (2) 4	15 (9) 18		
Rough handling and treatment	9 (5) 5	23 (11) 11			4 (4) 8	9 (7) 21

[a] Service life analysis from PDS Version 4.1; 48 by 40-inch pallets in a dry environment (≤19% equilibrium moisture content), multiple-use, new manufacture, double-face nonreversible partial four-way stringer pallet and double-face nonreversible full four-way block pallet.

[b] Life expectancy of the stringer pallet (26 cycles), total number of trips to the repair depot (6 trips), total number of components repaired or replaced during useful life (6 components).

[c] Life expectancy of the block pallet (30 cycles), total number of trips to the repair depot (7 trips), total number of components repaired or replaced during useful life (7 components).

Table 5.—Greenhouse gas emissions resulting from the refurbishment phase.

	Emissions (kg CO_2 eq/pallet)					
	Light-duty loads (1,000 lb)		Medium-duty loads (2,000 lb)		Heavy-duty loads (3,000 lb)	
Handling environment severity	Stringer	Block	Stringer	Block	Stringer	Block
Good handling and treatment	3.012	2.756			2.008	4.725
Average handling and treatment			1.532	4.813		
Rough handling and treatment	2.510	4.332			3.064	4.730

Table 6.—Greenhouse gas emissions and credits per end-of-life scenario.

	CO_2 eq emissions			CO_2 eq credits	
End-of-life scenario	Transportation to depot	Transportation to MSW/landfill/user[a]	Grinding process	Recycled steel	Recovered energy
Landfilling	Yes	Yes	No	No	No
Mulching	Yes	Yes	Yes	Yes	No
Incineration					
With energy recovery	Yes	Yes	Yes	Yes	Yes
Without energy recovery	No	No	No	No	No

[a] MSW = municipal solid waste facility.

End-of-life phase

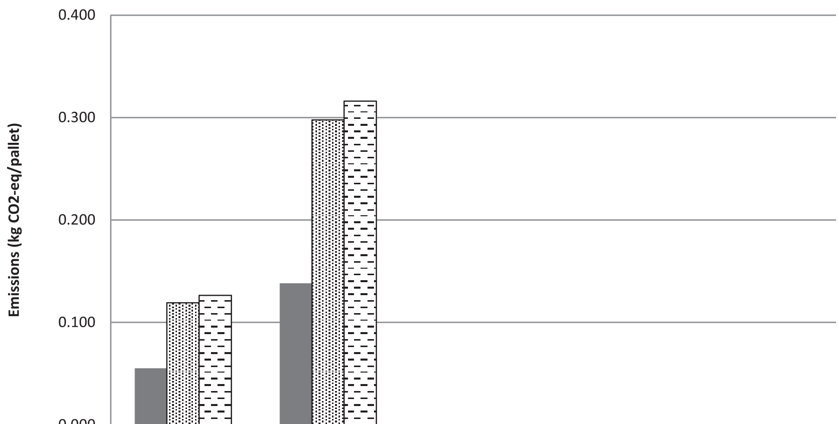
There are essentially four end-of-life scenarios that were observed to take place: landfilling, mulching, incineration with energy recovery, and incineration without energy recovery. The mix and occurrence of the four most common scenarios depend on the type of pallet management system as well as regional considerations at the point of disposal. The ability to control the end of life of large quantities of pallets and the associated environmental impacts of each scenario allow pallet-pooling companies to provide logistics arrangements that are attractive to those companies seeking to manage their carbon footprint.

Table 6 depicts the various activities occurring at the end of life of pallets that might incur GHG emissions or credits. Table 7 shows the unitary impact of disposing one pallet through the different end-of-life scenarios. Figures 2 through 4 depict the individual contributions of the each activity per type of pallet for landfilling, mulching, and incineration with energy recovery. The ''landfilling'' scenario refers to the direct disposition of used pallets into landfills. The ''mulching'' scenario refers to operations where used pallets are shredded, the steel material from fasteners is separated from the wood chips and recycled, and the wood is reused as landscaping material or animal bedding. The ''incineration with energy recovery'' scenario occurs when end-of-life pallets are shredded, the steel is recovered for recycling, and the wood material is burned to provide heat energy. The ''incineration without energy recovery'' scenario does not present any meaningful impact, as it typically takes the form of on-site open-pit fires of whole pallets that return the carbon sequestered by the wood into the atmosphere. When pallets are incinerated without energy recovery, the steel from fasteners and plates is not typically recovered or recycled; therefore, Table 6 shows no GHG credits for recycled steel under this method. This practice was not observed to take place in the Northeast, where climatic conditions and energy costs encourage heat recovery, but occurs with some frequency in rural areas of the Southeast and Midwest.

Figure 2 shows the impact of the two activities involved in landfilling: transportation to the depot and further transportation to the landfill. This shows the heavier tare weight pallets having a larger impact than lighter ones over the same distance. Figure 3 shows the impact of the activities involved in mulching: transportation to the depot, grinding process, and subsequent transportation to the final destination. It can be seen that the emissions from an industrial grinder are not sensitive to the small differences in mass across pallet types; hence, all pallet-grinding operations cause the same impact. A credit is established as a consequence of the salvaged steel from fasteners. In this graph, the original number of fasteners used at manufacturing was assumed, but realistically, plates will likely be added to stringer-based pallets, thus increasing this credit. To assess this, a specific service environment condition needs to be assumed so that the predicted number of plates installed on a pallet by disposal time can be estimated. Figure 4 is shown in a scale that highlights the large credit associated with the energy recovered from pallet lumber incineration and consequent avoidance of fossil fuel emissions. This uses the embodied energy of the wood prior to any processing and assumes 25 percent efficiency in recovery from the combustion. With the higher density and higher embodied energy of the hardwood, the stringer pallet produces a larger credit than the alternatives. It should be noted, however, that the differences are small and that other

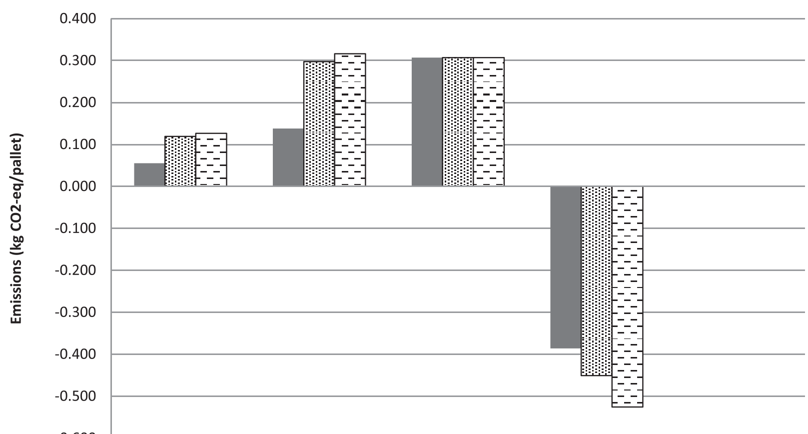
Table 7.—Unitary greenhouse gas emissions per end-of-life scenario.

	Emissions (kg CO_2 eq/pallet disposed)		
End-of-life scenario	Expendable	Stringer	Block
Landfilling	0.193	0.417	0.442
Mulching	0.114	0.273	0.223
Incineration with energy recovery	−7.580	−19.302	−18.336
Incineration without energy recovery	0.000	0.000	0.000



	Transport to depot	Transport to final destination	Grinding process	Recycled steels	Recovered energy
Expendable	0.055	0.138	0.000	0.000	0.000
Stringer	0.119	0.298	0.000	0.000	0.000
Block	0.126	0.316	0.000	0.000	0.000

Figure 2.—Individual activity contributions during landfilling of wood pallets.



	Transport to depot	Transport to final destination	Grinding process	Recycled steels	Recovered energy
Expendable	0.055	0.138	0.307	-0.386	0.000
Stringer	0.119	0.298	0.307	-0.451	0.000
Block	0.126	0.316	0.307	-0.526	0.000

Figure 3.—Individual activity contributions during mulching of wood pallets.

pallet designs, with a different mix of hardwoods and softwoods, may produce different amounts of credit.

It should be noted that, although four end-of-life scenarios were detailed, a company that uses a large quantity of pallets in their supply chain will likely engage, directly or indirectly, in all of these scenarios. One survey of 103 pallet recyclers in North Carolina found that 20 percent of the pallets received were reused, 45 percent were refurbished, 19 percent were recycled, and 15 percent were ground (Buehlmann et al. 2009). In a different study (Bush and Araman 2009), a survey of 590 facilities engaged in repair and recycling reported that 10 percent of the pallets were reused without repair, 67 percent of the pallets were repaired, 15.70 percent were dismantled (mostly for components), 6 percent were ground or chipped, 0.20 percent were landfilled, and 1.10 percent were unaccounted for.

This raises two important questions that are pivotal for estimating and controlling the end-of-life impacts of wood pallet operations: (1) What percentage of the pallets end up meeting each scenario? and (2) Can the pallet user design and determine the end-of-life scenarios so that it is possible to manage the footprint of the entire operation? Clearly, open-loop systems (such as the one that governs single-use expendable pallet systems) offer very limited opportunities to control the end of life, while closed-loop pallet pools provide take-back logistics that could offer the opportunity to control and design the end-of-life disposition.

Conclusions and Future Work

In this article, a detailed investigation of the operations and practices that take place in the wood pallet life cycle are presented, and a prescribed approach for quantifying the GHG impacts is proposed and illustrated. The estimation presented here allows for calculation of the contributions of

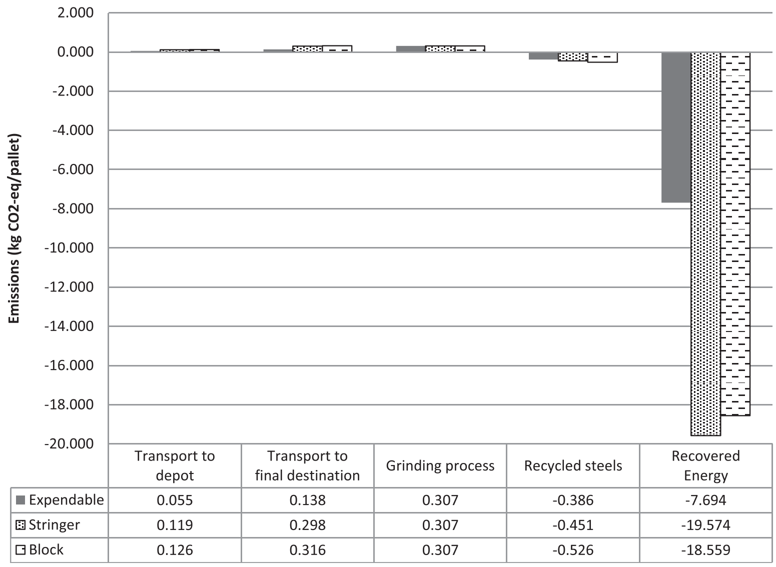


Figure 4.—Individual activity contributions during incineration (with energy recovery) of wood pallets.

the individual factors in each life-cycle phase. In the premanufacturing materials phase, wood accounts for the majority of the impact (an average of 82% across all pallet types) of the total CO_2 eq emissions, while steel is responsible for the remaining 18 percent. In the manufacturing phase, the emissions are derived largely from the heat treatment process (an average of 72% when heat treatment is applied to the pallets) as opposed to the assembly, which accounts for a small fraction of the total impact (35% expendable, 28% stringer, and 21% for block pallets). In the use and transportation phase, the impact is directly proportional to the tare weight of the pallet and the transportation mode. In the refurbishment phase, the individual contributions to the GHG emissions for stringer pallets are materials (47%), transportation (41%), and equipment (12%), while for the block pallets, the individual contributions are materials (28%), transportation (55%), and equipment (17%). In the end-of-life phase, the impacts range widely based on the dominant scenario of disposal. The analyses presented in this article should provide useful information to all stakeholders in the pallet logistics system, including manufacturers, users, and pooling providers. Companies seeking to reduce the impact of their pallet logistics operations may consider specific initiatives, depending on which phases appear to be the most influential in their respective activity impact profiles. For example, it has been previously shown that a light-weighting strategy on packaging can lead to reductions of 9 percent on related emissions, while a material substitution strategy can provide an additional 10 percent reduction (Hekkert et al. 2000). Although this study covered a wide range of packages, including bottles, cans, and other energy-intensive packages, an example can be found in corrugated boxes. In this type of packaging, an estimated reduction of 20 percent of

Table 8.—Strategies per dominant impact phase.

Dominant phase	Potential actions
Raw material	• Potential pallet light-weighting strategies focused on wood weight reduction (as opposed to metals) • Evaluation of a material substitution strategy (e.g., alternative wood species and alternative materials, such as plastic, corrugated, etc.) • Sourcing raw materials from geographically closer suppliers
Manufacturing	• Evaluation of alternative structural designs • Evaluation of number and type of steel fasteners • Comprehensive needs assessment of energy-intensive pallet treatments (in particular, kiln drying and heat treatments) • Incorporation of carbon-neutral energy sources in manufacturing
Use	• Potential pallet light-weighting strategies • Strategic pallet inventory positioning for nearby reallocation • Improved design of unit loads • Training of employees on best pallet-handling practices
Refurbishing	• Evaluation of the pallet repair depot location • Minimization of repair materials and processes • Standardization of sortation criteria
End of life (EOL)	• Selection of pallet providers and recyclers based on their EOL practices • Improved reverse logistics of empty pallets • Incorporation of energy recovery at pallet EOL • Consideration of third-party logistic providers with increased retention rates from nonparticipant distributors.

material content was shown to be feasible through elimination of redundant material and use of thinner materials. Other approaches can be considered. However, there must be an understanding of the trade-offs caused while proposing improvements. For example, Gasol et al. (2008) found that, for certain reuse intensities, a reduction in wood consumption caused an increase in the maintenance component (repair and replacement). Table 8 presents a list of suggested strategies for each situation. The findings in this article should support decision making for all these stakeholders throughout their supply chains and at the various phases of the pallet life cycle.

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