Investigation of the Environmental Effect of Unit Load Design Optimization Using Physical Interaction Between Pallets and Corrugated Boxes

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ACADEMIC ABSTRACT

Packaging sustainability has become one of the most notable issues of this era. Many researchers have endeavored to characterize or compare the environmental burdens of a single level of packaging, such as primary, secondary, or tertiary packaging. However, goods are often handled, stored, and transported through the supply chain system in unit load form consisting of pallets, corrugated boxes, and load stabilizers. Hence, it is important to holistically understand the environmental impact of not only individual packaging levels, but also the unit load form. We can use the interactions between the unit load components to reduce the environmental burdens generated in the supply chain system.

Past studies discovered that pallet top deck thickness has a huge effect on corrugated box compression strength. Using this knowledge, researchers were able to optimize the cost of unit loads by increasing pallet top deck thickness and reducing the board grade of corrugated boxes. This study (1) further discovered how different unit load design factors, such as initial top deck thickness, pallet wood species, box size, and board grade, affect the performance of the previously proposed unit load design optimization method, and (2) we investigated if the unit load optimization method could also enhance unit load sustainability.

The study's first phase identified that the benefits of increasing top deck thickness were more pronounced as the initial top deck thickness decreased, higher board grade boxes were initially utilized, and smaller-sized boxes were used. The second phase of this study showed that increasing top deck thickness and reducing the board grade of corrugated boxes could offset environmental impacts by as much as 23%. Environmental benefits were mostly achieved by reducing the amount of relatively more-processed materials in the corrugated boards. This phase also provided preliminary unit load conditions as guidance for unit load professionals to estimate the possibility of optimizing their unit load design in an environmentally beneficial way.

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GENERAL AUDIENCE ABSTRACT

Sustainability-minded individuals, industries, and policymakers recently recognized the environmental burdens associated with packaging as a critical concern to society. Many initiatives and studies have been conducted to prevent and reduce the environmental impacts of individual packaging systems, such as corrugated boxes, plastic bottles, and pallets. However, not many efforts have been made to enhance the environmental performance of a whole unit load, which is the most common distribution packaging form used to transport and store goods. It is essential to understand the physical interactions between unit load components, such as corrugated boxes and pallets, in order to improve a unit load's environmental performance effectively.

The unit load optimization concept introduced in the past study, which showed that increasing top deck thickness can reduce the needed board grade of corrugated boxes, was further investigated and utilized in this study to offset the environmental burdens of a unit load by substituting different materials used. To assess the environmental performance of that unit load design optimization method, this study first endeavored to understand further how various unit load design factors could affect the result of unit load optimization, and second, we analyzed many different scenarios using a life cycle analysis method.

The study found that the unit load design method that uses deck board thickness to change the amount of corrugated board needed had more potential for lighter pallets with thinner deck boards carrying heavier loads. The results also showed that increasing top deck board thickness and reducing the board grade of the corrugated board could improve the environmental performance of a unit load when the corrugated material is sufficiently substituted with a reasonable amount of pallet material.

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Table of Contents

1 Chapter 1: Literature Review

1.1 Wood Pallets

1.1.1 Introduction of Wood Pallets

A pallet is defined as "a portable, horizontal, rigid, composite platform used as a base for assembling, storing, stacking, handling, and transporting goods as unit load" by the Material Handling 1 Committee of the American National Standards Institute (ANSI, 2019). The pallet has a long history of over 100 years (Mokhlesi & Andersson, 2009). However, it became the most important basic component of the material handling system in the 1940s during World War II. The introduction of forklifts during the war made having a pallet as a base the most efficient way to handle materials in a unitized form which contributed tremendously to the success of the war for the U.S. (Grob, 1973). The evolution of the pallet did not occur all at once. The poor performance of crude skids, which were constructed of a simple deck board and stringers, as material carriers for heavy unit loads, along with the introduction of the forklift, played significant roles in creating the desire for a better platform in the material handling environment. By coming up with standards for pallet construction and the continuous improvement of material handling machines, the pallet started playing a very vital role in increasing the efficiency and reliability of the modern supply chain (Mokhlesi & Andersson, 2009).

The most common unit load platform for the handling and storage of items in the supply chain today is the pallet (Bilbao et al., 2011). The worldwide pallet production industry is worth billions of dollars, and it keeps increasing (Freedonia, 2017). The U.S. has the largest market share of the worldwide pallet industry. The U.S. is estimated to need 28.5% of world pallet supply in 2012 (Freedonia, 2017). Total pallet use in the U.S. has been estimated to grow continuously at a rate of 1.9% annually until it reaches 2.6 billion units. Demand itself is estimated to grow to 1.4 billion units by 2019 (Freedonia, 2017). Freedonia (2017) also estimated that the wood pallet would be dominant in the market and consist of about 84% of the total pallet stock by 2019. The number of new, wood pallets produced in the U.S. market keeps growing. Five hundred eight million new wood pallets were produced in the U.S. market in 2016, and that shows an increase of 22%

compared to 2011 (416 million units) (Gerber et al., 2020). The number of recycled or remanufactured wood pallets has remained constant since 2011; at the very high number of 326 million units (Gerber et al., 2020).

1.1.2 Classification of Wood Pallets

The classification of wood pallets can be described by two main classes: stringer class pallets (Figure 1.1.) and block class pallets (Figure 1.2.).

Stringer Class Pallets

Stringer class pallets are the most common pallet class in the United States and the most newly produced class of wood pallets. Gerber, Horvath, and Araman (2020) reported that 76% of newly constructed wood pallets were stringer class pallets. Stringer class pallets consist of top and/or bottom deck boards, at least two stringers, and different types of fasteners, such as nails, staples, screws, bolts, lag bolts, adhesives, and/or welds (ANSI, 2019). Stringers are one type of pallet component: they are a solid or notched wooden beam that gives support and spacing ability to the deck boards (ANSI, 2019). Usually, these wooden beam components are built 3.5 in x 1.5 in. (height x width), and this makes the stringer class pallets commonly have 3.5 in. openings (Quesenberry, 2020). Stringer class pallets can be broken down further into 2-way designs or partial 4-way designs; this indicates the number of side openings available for forklifts or pallet jacks to enter by their fork tines. Two-way designs do not have notches on their stringers; hence, limits entry from the stringer sides for both forklifts and pallet jacks. Partial 4-way designs are ones that have notches on their stringers that only allow forklifts access from the stringer side, but not pallet jacks, due to the low height of the notches (Park, 2015).

Stringer class pallets can also be further classified through their face construction style: single-face, reversible double-face, and nonreversible double-face (NWPCA, 2014). Single-face, stringer class pallets (commonly called skids) consist of top deck boards, stringers, and fasteners without bottom deck boards. Reversible, double-face, stringer pallets have identical top and bottom deck board designs which makes these pallets able to be used from either side just by flipping them over. This style can be adapted to the stringer class pallets because solid non-notched stringers support both the top and bottom

deck boards. Nonreversible, double-face pallets are usually constructed with more deck boards on the top and fewer deck boards on the bottom, so it has a designated top and bottom side to the pallet (Morrissette, 2019).

The stringer class pallets have different names for various alignments of the top and bottom deck boards. Flush pallets have top and bottom deck boards aligned across the direction of the stringer. If only top deck boards overhang the stringers, they are called single-winged pallets, and if both top and bottom deck boards overhang the stringers, they are called double-winged pallets (ANSI, 2019). The direction of the bottom deck boards can be unidirectional, overlapping, perimeter, or cruciform (ANSI, 2019).

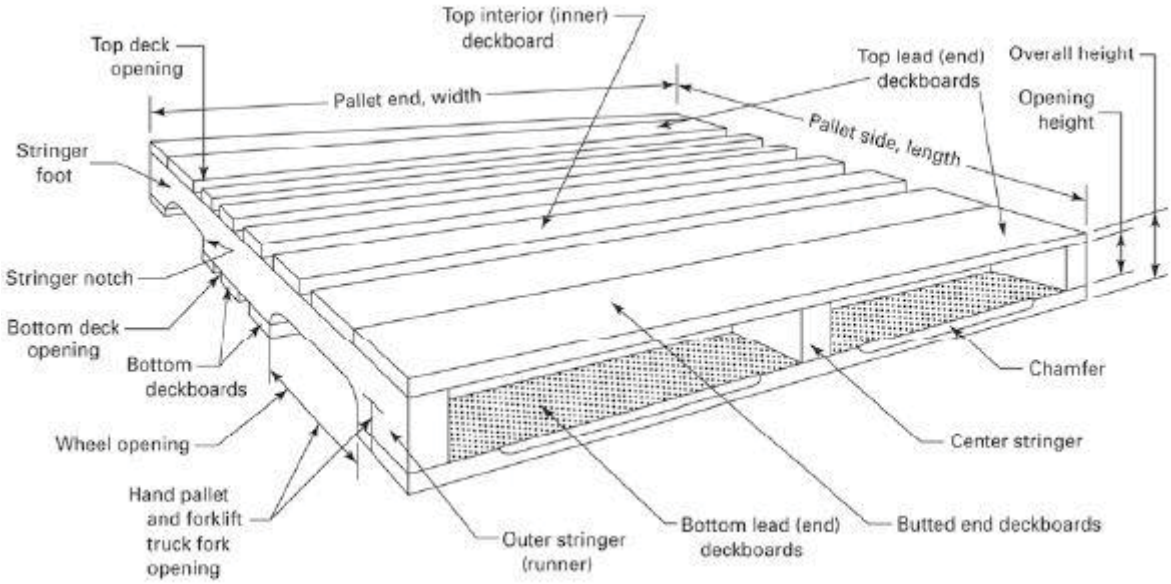

Figure 1.1. The basic structure of the stringer class pallet: adapted from ANSI (2019).

Block Class Pallets

Block class pallets are usually constructed with top and/or bottom deck boards, fasteners, nine wooden blocks, and stringer boards (ANSI, 2019). Unlike stringer class pallets, block class pallets have a full 4-way design which makes it fully accessible from all four sides of the pallet. Block class pallets usually do not have a reversible, double-face design, but all three types of face construction styles, discussed above, are available: single-face, reversible double-face, and nonreversible double-face. Regarding deck board alignment, block class pallets also share the same names for the different types of the winged pallets, but they depend on the direction of stringer boards instead of stringers (ANSI, 2019).

Block class pallets have the advantages of durability and full four-way accessibility. Due to these advantages, many of the retailers and wood pallet pooling companies, such as Wal-Mart, Costco, or Commonwealth Handling Equipment Pool (CHEP), prefer to use block class pallets even they have a higher manufacturing cost and require more materials than stringer class pallets even when they have the same strength (Park, 2015).

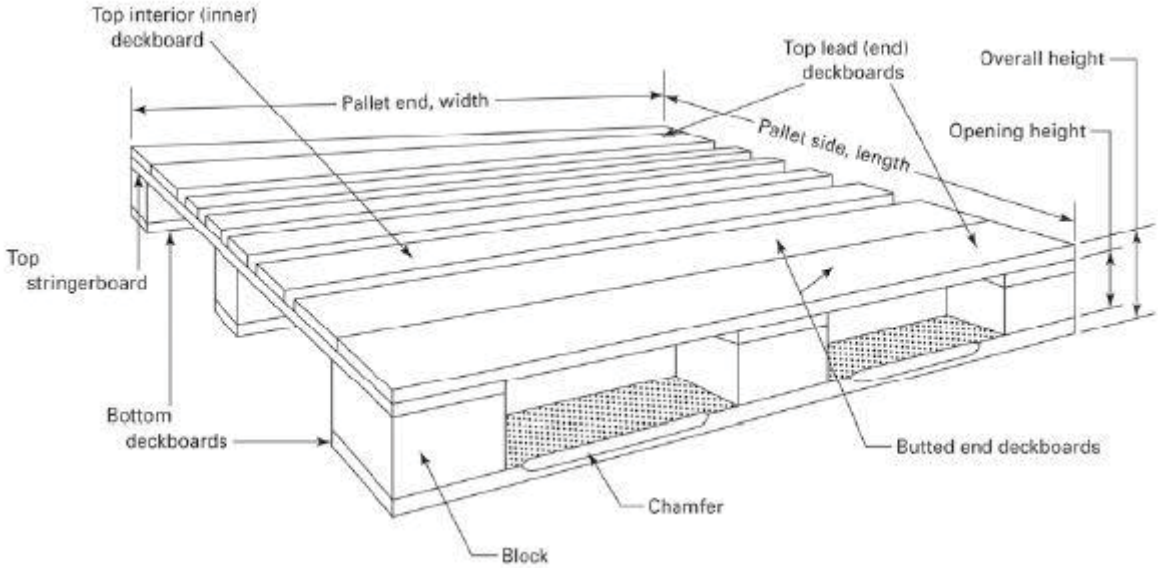

Figure 1.2. The basic structure of block class pallet: adapted from ANSI MH1 (2019).

Intended Use

Wood pallets also can be classified from the usability perspective into two use categories: single-use pallets and reusable pallets. Single-use pallets are made to be used once and then be disposed of or recycled. No refurbishment or repair is expected during its life cycle. Reusable pallets are constructed with more durable designs and materials. They are used at least two times, but optimally, several times in a closed-loop system (ANSI, 2019).

1.1.3 Sizes of Wood Pallets

The size of wood pallets is identified by the stringer/stringer board length, followed by the deck board length (Clarke, 2004). Many different sizes of wood pallets exist around the world today. The standard pallet size varies industry to industry and region to region. For example, the grocery industry mostly uses 48 in. x 40 in. pallets, drums require a 48

in. x 45 in. pallet, and the beverage industry commonly uses 37 in. x 37 in. pallets (Clare, 2004). Also, in the regional context, Western Europe uses the 800 mm x 1200 mm EuroPallet as their standard pallet, and the 48 in. x 40 in. GMA style pallet is dominant in the United States (Clarke, 2004). The 48 in. x 40 in. size pallet accounts for 35% of all new, wood pallets constructed in the U.S. This is an 8% increase from 2006 (Gerber et al., 2020). A trend of increasing 48 in. x 40 in. pallet production has been observed over the last 10 years (Gerber et al., 2020). Several possible reasons could explain this trend. For instance, industry consolidation eliminates smaller pallet companies focused on producing custom sizes. The industry naturally requires a transition toward standardization of size (Gerber et al., 2020). The industry has started to standardize the global pallet size as 1200 mm x 1000 mm size pallet, which is very close to the 48 in. x 40 in. in the U.S. This is increasing the efficiency of production and transportation, domestically and internationally (Clarke, 2004; Park, 2015). Table 1.1. presents an estimation of what sizes of new wood pallets were manufactured in the U.S. between 2006 and 2016.

Table 1.1. Estimated percentage of new wood pallet sizes produced in the U.S. between 2006 and 2016 (Gerber et al., 2020).

Year	48”x 40”	40”x 48”	48”x 48”	48”x 45”	48”x 42”	48”x 36”	42”x 42”	37”x 37”	800x1200 mm	other
2006	27%	5%	4%	2%	4%	2%	5%	2%	-	50%
2011	24%	3%	4%	-	-	2%	5%	2%	1%	60%
2016	35%	4%	1%	5%	3%	1%	5%	<1%	1%	39%

1.1.4 Materials of Wood Pallets

The most common material for the pallet in the U.S., with about 90%- 95% of the market, is wood (Buehlmann et al., 2009; Carrano et al., 2014; Gerber et al., 2020). Wood materials are dominantly used in the pallet industry in the U.S. because of the low material and production costs and many other advantages, such as the abundance of nature, configuration of components that can be easily modified during the manufacturing process, and durability (Buehlmann et al., 2009; LeBlanc & Richardson, 2003). The wood pallet industry mostly consumes lower grade woods due to their relatively low

costs (Buehlmann et al., 2009). In the U.S., 21.8% of total new lumber produced was used to manufacture both new and repaired pallets in 2016 (Madison's Lumber Reporter, 2017). Ninety-four percent (94%) of new wood lumber used for pallet manufacturing and repair in the U.S. was produced domestically. Only 6% was imported, and 99% of imported lumber came from Canada (Gerber et al., 2020).

Softwoods and hardwoods are both used to construct wood pallets. Hardwood lumber is historically preferred as pallet material over softwood lumber, but recent trends show softwood is taking some of the demand from hardwood. In 1995, the U.S. pallet industry utilized 71.7% hardwoods to construct new wood pallets, but that number has decreased to 63.6% in 2006 (Araman et al., 2006). Many different softwood and hardwood species are used for manufacturing and repairing wood pallets depending on their geographical regions and due to cost efficiency (Quesenberry, 2020). Manufacturers usually purchase wood from local suppliers, since wood is a very low-cost material, making manufacturers limited to local species for their pallet construction (Quesenberry, 2020). Figure 1.3. shows the specific species used in each region depending on their availability. Nationwide, mixed hardwood species (61.2%) were mainly used to construct hardwood pallets, followed by oak, maple, and other hardwood species (Araman et al., 2006). For the softwood pallet, the southern pine species group accounted more than half of total softwood use by volume (53.5%), followed by the spruce, pine, and fir species group (Araman et al., 2006).

Figure 1.3. Wood species used for pallet manufacturers in the United States from different regions; adapted from Park (2015).

The moisture content of lumber is one of the important variables that can affect the strength of wood (ASTM International, 2010). The dimension of green wood is never truly fixed because it shrinks and swells since it has not been dried. It is considered to have 100% moisture content relative to dried wood. The hardwood pallet usually uses green lumber, and sometimes, this causes a mold problem on the pallet. Softwood pallets often uses kiln-dried lumber, which reduces the mold problem. The kiln-drying process dries wood in a large oven until the moisture content drops below 20% (Quesenberry, 2020).

1.1.5 Phytosanitary Treatments of Wood Packaging Materials

Wood packaging materials used for wood pallet components are usually unprocessed, raw wood that could spread pests. The uncontrolled spread of pests could significantly affect local, natural systems such as agriculture, forestry, industry, and human health (Anil Philip, 2010). A phytosanitary treatment process needs to be applied to the debarked wood to kill or eradicate potentially invasive pests from the wood materials.

When the wood packaging is intended for international shipping, International Standard for Phytosanitary Measures No. 15 (ISPM 15) regulates this treatment. ISPM 15 is a document by the Commission on Phytosanitary Measures (CPM), which was established by the Food and Agriculture Organization of the United Nations (FAO), and provides guidelines for the phytosanitary treatments of wood packaging such as pallets, crates, boxes, and dunnage. Currently, two different treatment methods are approved under International Standards for Phytosanitary Measures Publication No. 15 (ISPM 15): heat treatment and methyl bromide fumigation. Wood pallets treated using these two methods are marked with a stamp that records the country code, treatment provider code, and the treatment type code (Figure 1.4.).

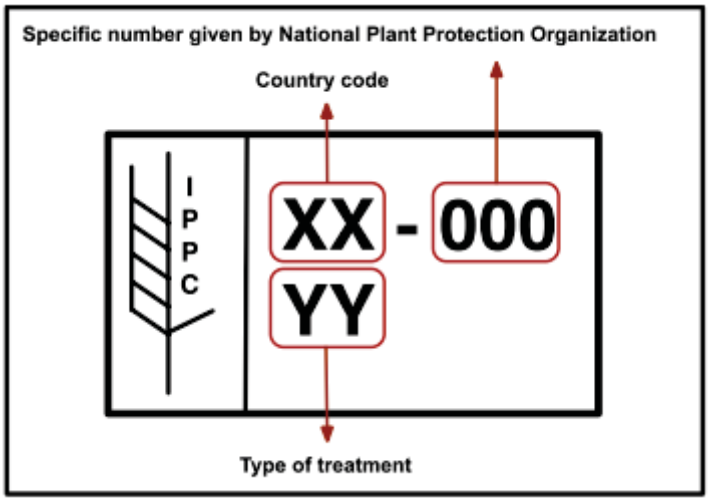

Figure 1.4. Example of ISPM 15 Certification stamp with code information (IPPC, 2017; Park, 2015).

Heat Treatment

The energy for heat treatment could come from various sources such as conventional steam heating, kiln-drying, heat-enabled chemical pressure impregnation, and dielectric heating (microwave or radiofrequency) (International Plant Protection Convention (IPPC), 2017). Using conventional or kiln-drying heat chamber technology requires maintaining a minimum of 56 °C wood core temperature and a minimum duration of 30 continuous minutes and marked as 'HT' treatment code with a stamp. On the other hand, dielectric heating technology requires maintaining the wood core and surface heated at 60 °C for

one minute and reaching this temperature within 30 minutes of the start of the treatment. Wood material heated using dielectric heating technology will be marked with the treatment code 'DH' (IPPC, 2017).

Methyl Bromide Fumigation

Wood pallets also can be treated using methyl bromide fumigation. This process requires fumigating wood pallets with methyl bromide for at least 24 hours at a temperature of no less than 10 ℃. Records of the methyl bromide gas concentration should be taken at 2, 4, and 24 hours from the start of the process. If the process has a duration longer than 24 hours and weaker gas concentration, then records have to be taken one additional time at the end of the fumigation (IPPC, 2017). This method of treatment is recommended to replace or reduce the suspected toxicity found by the North American Plant Protection Organization (NAPPO) (Commission on Phytosanitary Measures Recommendation (CPM), 2017).

1.1.6 Manufacturing Process of Wood Pallets

The typical manufacturing process for wood pallets is as follows: log harvesting with bark, transport of raw materials to a processing site, radius sorting, length and shape sorting, transport to the manufacturing site, shaping logs into boards, stringers, or blocks, notching stringers for the partial 4-way, stringer class pallets, phytosanitary treatment, pallet assembly, groove milling, sawdust collection, chipping, and pallet drying (thermal energy mainly generated from wood chips) (Kočí, 2019).

When the trees have reached the desired height, they are harvested by machines and logs are produced. After harvesting, the logs are transported from the forest to the sawmill, usually by trucks. Logs get sorted depending on their diameters, and they get debarked after sorting. These debarked logs get cut to sizes about 2.5 m to 4.0 m starting from the base. Now they are sorted into the shapes and lengths needed for cutting into pallet parts, such as the top and bottom deck boards, stringers, stringer boards, and/or blocks. At this point, many wastes are generated, such as sawdust, bark, and scrap chips. After using them as a thermal energy source, leftover chips are usually sold as a by-product. After all

the materials are shaped, the pallet is assembled and goes straight into the drying room (Kočí, 2019).

The wood pallet manufacturing process and equipment have become more and more automated and developed over time. Wood pallet production can be broken down into three types depending on equipment use and automation levels: manual, semi-automatic, or automatic. Until the mid-1950s, pallet assembly was mostly done by hand-nailing using a table and hammer (LeBlanc & Richardson, 2003). This manual process required a well-trained, two-man crew who constructed 60 to 75 wood pallets daily. The industry required reduced board-splitting problems and increased productivity (LeBlanc & Richardson, 2003). Chain-fed pre-drilling machines, pneumatic hammers, and pallet assembly machines have been introduced to meet these requirements and minimize manual operations (LeBlanc & Richardson, 2003). Due to the emergence of automated machines, the daily productivity of pallet assembly increased up to 2000 pallets per day (Viking Engineering, 2014). Carrano et al. (2014) also agreed that automated pallet production increased productivity; the manual process takes nearly 2 minutes per pallet. The semi-automated process takes 1.5 minutes per pallet, and the fully automated process takes approximately .5 to 1 minute per pallet.

1.1.7 Recovery, Repair, and Refurbishment of Wood Pallets

After manufacturing the new wood pallet, it gets shipped to different locations carrying products from manufacturers, retailers, or even pallet pooling companies. It is impossible to avoid the damages to new wood pallets that happen while going through the supply chain. When a wood pallet gets damaged or broken, it does not just go to the landfill, but if it is recyclable, repairable, or recoverable, it goes to a recycling facility. The recycled, recovered, and remanufactured wood pallet industry has shown rapid growth in the U.S. of 127% from 1995 to 2011 (Araman et al., 2006; Gerber et al., 2020). The same number of wood pallets recycled in 2011 (326 million pallets) was found to have been continuously recycled every year through 2016 (Gerber, 2020). The number of landfilled wood pallets per municipal solid waste (MSW) facility decreased by 78.9%, from 1,269 tons in 1995 to 267 tons in 2016, which correlates to the recycled, recovered, and remanufactured wood pallets' increasing industry share, as mentioned before (Shiner,

2018). According to Shiner (2018), 45.2% of pallets received at MSW facilities were landfilled in 2016, and 54.8% of pallets were reused, recovered, repaired, or refurbished. Among non-landfilled pallets in 2006, 67% were repaired, 15.7% were un-nailed and disassembled for component recycling, 10% were reused without any repair process, 6% were ground or chipped, and 1.1% were used for other purposes (Bush & Araman, 2009).

The repair process for wood pallets mostly includes adding additional components to support the damaged point of the pallet; for instance, adding companion stringers or metal plates to cracked stringers (Park, 2015). However, no standard guide exists for the pallet repair process. Manual repairing methods still exist in the industry, as well as semi-automatic and fully automatic processes. There are three common systems for pallet repair: straight-line system, over and under the system, and build on the fly system (Leising, 2003). The straight-line system uses a slider-bed, conveyor-belt system that allows various pallet sizes to be repaired and collects 100% of wood scraps along the repair process. The over and under system consists of a roller-type conveyor, a dead-roller conveyor, and a scrap conveyor that requires 4-6 builders on a line. It is faster than the straight-line system but can only operate on a single sized pallet at a time. The build on the fly system is a mixed version of the two previous systems. It has the fastest productivity, but could produce poorer repair quality and could be more expensive (Leising, 2003).

1.2 Corrugated boxes

1.2.1 Introduction of Corrugated Boxes

A corrugated fiberboard box is the dominant packaging material used nowadays. The corrugated fiberboard industry made $26.1 billion in 2011 (Twede et al., 2015). About 95% of North American consumer products are packaged in corrugated fiberboard boxes (Fibre Box Association, 2015). The corrugated fiberboard box is commonly used for the purpose of storage, shipping, and protection. Sometimes, it also can bring sales and marketing benefits (US EPA, 2018).

The history of corrugated materials started in England in 1856 with the first corrugated material patent issued as a fluting material for cushioning the liner of hat sweatbands

(Fibre Box Association, 2015). The first application of corrugated materials to the packaging was a fluted paper used as a cushioning material for glasses. The corrugated material gradually evolved its structure by adding flat paper called liners and fluted paper called mediums (Fibre Box Association, 2015). The combination of a single liner and fluted paper, called single-face design, was first introduced in 1874. Today's common corrugated board structure, double-face design, is the sandwiched structure of two liners and one medium in between. This appeared in the late 1870s. The automation of double-face, corrugated paperboard production became available in 1895 (Fibre Box Association, 2015). Finally, corrugated paperboard started to be transformed into the common box shape through slotting, creasing, and cutting in 1894. It became famous as a packaging material through many different events, such as its approval as railroad packaging in the early 1900s (Fibre Box Association, 2015). Nowadays, corrugated paperboard has become the predominant material used for most product distribution and storage (Frank, 2014). Corrugated boxes account for about 80% of paper packaging volume in the U.S. (Twede et al., 2015).

1.2.2 Corrugated Board Structure and Related Terms

Corrugated paperboard is defined as a board consisting of one or more fluted papers (called mediums), glued to a flat sheet of board, known as a liner, or between several flat sheets (International Organization for Standardization (ISO), 2016). The number of mediums and liners decide the structural naming for corrugated boards. For example, a "single wall corrugated board" consists of two liners and one medium, or a "double wall corrugated board" consists of three liners and two mediums (Figure 1.5).

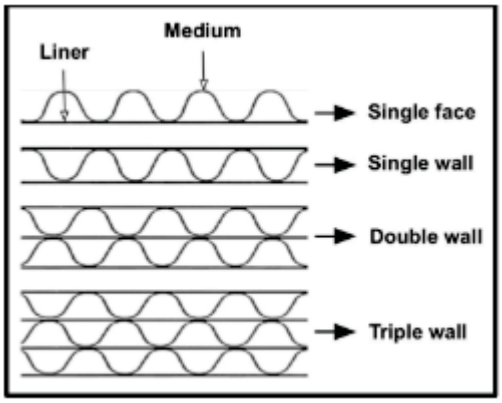

Figure 1.5. Types of corrugated fiberboard structures (Park, 2015)

Corrugated paperboard thickness is referred to as its caliper, and includes both mediums and liners. Box compression strength is often crucially affected by the boards' caliper (Park, 2015). Common flute sizes exist in the industry: A, C, B, and E flute. A, C, B, and then E is the order of caliper/thickness from largest to smallest. A flutes are the thickest, and were the first flute size ever made (Fibre Box Association, 2015). The next thickest flute size is the C flute, followed by the B, and finally the E flute (Fibre Box Association, 2015). Different flute sizes are used for different purposes. A flute provides great cushioning for fragile products since it is the thickest flute size. C flute is generally used for shipping containers, and E flute is often used as an alternative to paperboard folding cartons (Pro Pac, n.d.).

Corrugated paperboards are usually marked or specified by basis weight as well. Basis weight indicates the weight of the paper per unit area including liners and mediums (Technical Association of the Pulp and Paper Industry (TAPPI), 2013). Basis weight is measured in pounds per thousand square feet of paper. The board grade is generally marked in order of outside liner/medium, flute type, then inside liner (e.g. 38/33C/38) (Park, 2015). Basis weight is commonly used to predict the mechanical properties of the corrugated fiberboard, and it also refers to its quality (Park, 2015). The common basis weight of liners and mediums used in the industry are listed in Table 1.2.

Table 1.2. The common basis weight of liners and medium for corrugated fiberboards (Steadman, 2002).

Liner (lbs/1,000 ft^2)	Medium (lbs/1,000 ft^2)
26	26
33	28
38	30
48	36
47	40
69	42

1.2.3 Corrugated Board Properties

Many different properties of corrugated fiberboard can be tested and measured using various types of testing methods. Existing standardized testing methods for evaluating corrugated fiberboard properties are the edge crush test, flat crush test, burst strength test, and flexural stiffness test.

The edge crush test is the testing method that evaluates the edgewise compressive strength (ECT) of corrugated fiberboard in a cross-machine direction (Figure 1.6) (Park, 2015). ECT is one of the most important factors affecting a corrugated box's compression strength (McKee et al., 1961). There are several standardized tests that can be used to measure ECT: the short column TAPPI T811, the neck down TAPPI T83, and the clamping method TAPPI T839. Among these tests, the short column TAPPI T811, which applies the test load parallel to the boards' flutes, is the most widely used standardized test (Park, 2015).

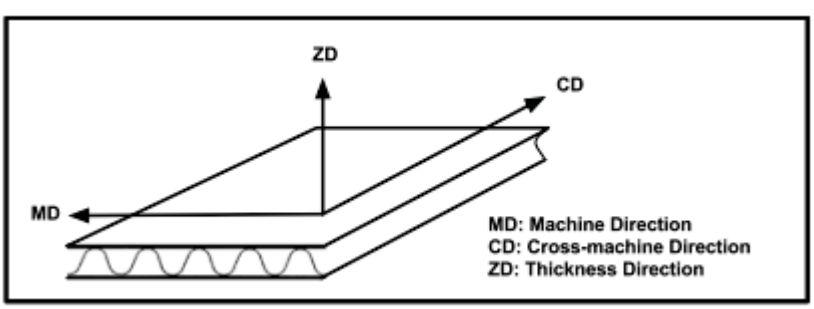

Figure 1.6. The direction of corrugated fiberboard (Park, 2015).

The flat crush test (FCT) (TAPPI T808) is a testing method to measure the strength of the corrugated board's medium by applying a compression force to the facing liners until the flutes get crushed. FCT is used to measure the cushioning performance of single-faced or single-wall corrugated fiberboard. FCT is not used on double-wall or triple-wall corrugated fiberboard because of the lateral motion of the central liners. FCT is conducted by placing corrugated fiberboard on top of one platen with the liner laying downwards and applying force with another platen from the top for 25 lbs./sec. until the flute is crushed.

The burst strength test (TAPPI T807), also called the Mullen Burst Test, measures the burst strength of corrugated fiberboard. The testing sample needs to be clamped between two platens with circular openings in their centers to conduct this test, and then hydraulic pressure is applied until the testing sample bursts.

The flexural stiffness test (TAPPI T820) measures the flexural bending stiffness of corrugated fiberboard. The flexural stiffness of the corrugated fiberboard is one of the important factors used to estimate the compression strength of the corrugated fiberboard box (Lee & Park, 2004; McKee et al., 1963). To conduct this test, a four-point bending method is preferred over the other types of bending test methods, such as two-point or three-point bending testing, because the four-points bending test set-up can prevent shear stresses that can occur on the central span between two, middle support points (Lee & Park, 2004).

1.2.4 Corrugated Box Styles

Corrugated paperboard boxes structurally consist of several sidewall panels, as well as major and minor flaps at the top and bottom openings (Quesenberry, 2020). There are many different standard structural design styles for corrugated paperboard boxes. These standard styles and the numerical code systems for these styles were defined and developed by the European Federation of Corrugated Board Manufacturers (FEFCO) to minimize the chance of errors when communicating in different languages. Of the numerous standard box styles, the regular slotted container (RSC), which is numerically coded as #0201, is most commonly used (Fibre Box Association, 2015; McKee et al.,

1961; Twede et al., 2015). RSC boxes are constructed with all the same lengths of matching flaps regardless if they are outer or inner flaps. Outer (major) flaps are designed to be half of a containers' width, which makes the two outer flaps meet together in the middle of the box (Fibre Box Association, 2015). Other popular box styles are half slotted container (HSC, #0200) and full overlap slotted container (FOL, #0203) (Fibre Box Association, 2015). For special purposes, and to fit specific needs, corrugated box structures can also be customized to any size/style by packaging designers.

1.2.5 Corrugated Box Compression Strength

Corrugated boxes must have sufficient compression strength to withstand risks and protect their product from the compression hazards that arise from the distribution process. For this purpose, many studies have historically investigated the key factors that significantly affect box compression strength within the distribution system. Standardized testing methods for corrugated box compression strength were established by ASTM International (ASTM D642) and TAPPI (TAPPI T804).

McKee et al. (1963) came up with a formula that estimates the compression strength of corrugated boxes without manufacturing or testing the actual box using the standard conditions of 50% relative humidity and temperature of 73°F. This formula is also known as the McKee equation (Equation 1.1), and it is still the most widely used formula to predict corrugated boxes compression strengths. It mainly focuses on the ECT value as the most critical factor as it is directly related to the compression strength of the box (McKee et al., 1963).

$$P = 5.87 \cdot Pm \cdot \sqrt{h \cdot Z}$$

Equation 1.1 Simplified Mckee Equation

Where:

P = Total box load

Pm = ECT value

h = caliper of the corrugated board

Z = Box perimeter

However, the McKee equation can only be adapted to the RSC type boxes with tall enough sidewalls that they cannot be crushed from the short column test, which makes the McKee equation have the accuracy of +/- 15% for 95% of data (Baker, 2016).

Other factors not considered in the McKee equation that can affect a corrugated box's compression strength are categorized by material properties, manufacturing methods, and environmental condition factors.

The material properties that affect corrugated box compression strength are the basis weight of the corrugated board (Kellicut & Landt, 1958), size of the flute (McKee et al., 1963), the adhesive level (Frank, 2014; Popil et al., 2006), the printing method (Kawanishi, 1989), and the percentage of recycled content used (Almanza et al., 1993).

Various manufacturing methods were also found to be key factors affecting the compression strength of corrugated boxes. Manufacturing joints (J. Singh et al., 2009), flap designs (Kellicut & Landt, 1958; Urbanik & Frank, 2006), holes (Han & Park, 2007; Jinkarn et al., 2006; Kwak, 2010), and inserts (Surber & Catlin, 1982) are the manufacturing methods that affect compression strength.

The environmental conditions that affect the compression strength of boxes are as follows: load duration (Frank, 2014; Kellicut & Landt, 1958; Whitsitt & McKee, 1972), box overhang (DiSalvo, 1999), pallet gaps (Baker, 2016; DiSalvo, 1999), stacking patterns (especially interlock stacking) (Kellicut, 1963; Jay Singh et al., 2011), humidity (Kellicut & Landt, 1958; Whitsitt & McKee, 1972), handling conditions (Godshall, 1968; Marcondes, 1992; Urbanik & Frank, 2006), and pallet stiffness (Baker, 2016; Phanthanousy, 2017; Quesenberry, 2020; S. P. Singh et al., 2011; Yoo, 2011).

The effect of a pallets' top deck stiffness on corrugated box compression strength is a relatively recent finding made by several researchers: Baker, Phanthanousy, and Quesenberry, in particular. Baker (2016) and Phanthanousy (2017) investigated the relationship of the differences in stress concentrations to the corrugated box's compression strength. They concluded that pallet top deck stiffness has no effect on the compression strength of corrugated boxes when the pallet is designed with gaps between top deck boards. Baker (2016) found that top deck stiffness affects box compression strength when the pallet has no gaps between top deck boards with as much as a 26% difference. These experiments were done with all four box corners symmetrically

supported. However, Baker (2016) further found that an asymmetrical supporting condition in a unit load is very common, and boxes supported asymmetrically were 15% weaker than symmetrically supported boxes. Based on these findings, Quesenberry (2020) evaluated the effect of pallet top deck stiffness on the compression strength of asymmetrically supported corrugated boxes. He found that the asymmetrically supported boxes, when stacked on stiffer top deck boards, can have as much as 37% higher compression strength (Quesenberry, 2020).

1.2.6 Box Manufacturer's Certificate

A Box Manufacturer's Certificate (BMC) is a printed seal that shows the minimum material requirements that the box meets (Fibre Box Association, 2015). It also tells us if the box meets the minimum structural requirements of Item 222 under National Freight Classification (NMFC for truck transport) and Rule 41 under Uniform Freight Classification (UFC for rail transport) (Fibre Box Association, 2015). All BMCs must include the name and location of the certifying company, ECT or BCT, basis weight, gross weight, and size limits of the box. Figure 1.7 shows the example of BMC with the ECT value.

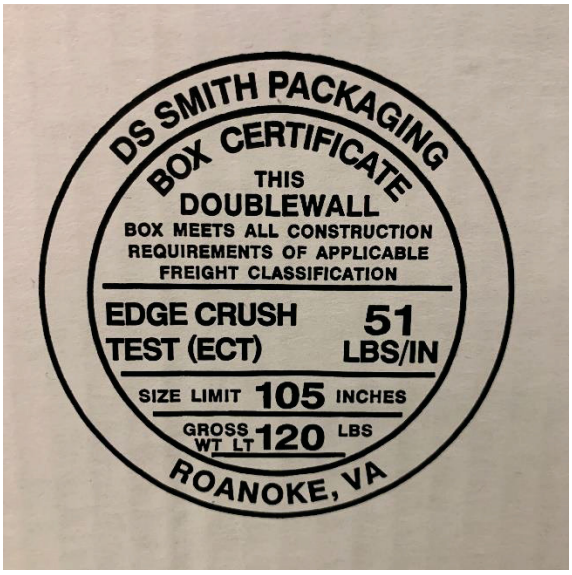

Figure 1.7. Box Manufacturer's Certificate displaying the ECT value

1.2.7 Manufacturing Process of Corrugated Boxes

The common manufacturing process of corrugated boxes can be explained in three main steps: fiber acquisition, pulp and papermaking, and converting (Gaudreault et al., 2020). Once trees are harvested, they get chipped and transported to paper mills.

When the materials are transported to the pulp and paper mills, the wood chips get debarked and pulped to remove the natural glue in the wood called lignin that binds the cellulose fibers together (Fibre Box Association, 2015; Gaudreault et al., 2020). To manufacture linerboard, a chemical pulping process is commonly used. Medium production, however, usually uses a semi-chemical process - a combination of chemical and mechanical processes (Fibre Box Association, 2015). Then the pulped materials go through the papermaking process that consists of web shape forming, squeezing out water, additional heat drying, and winding into a roll. Completed paper rolls then get shipped to the corrugated plant.

The last process for corrugated box manufacturing is converting. The three main stages of the converting process are corrugating the flutes, gluing them to the linerboards, and finally cutting the boards to the desired size (European Federation of Corrugated Board Manufacturers (FEFCO), n.d.). The machine used to manufacture corrugated board is called a corrugator. First, three or more webs of paper are fed into the corrugator simultaneously, and for mediums they are given a “wave” to make fluted paper (FEFCO, n.d.; Fibre Box Association, 2015). Next, the outer and inner liners and the now-fluted paper are glued together using corn or wheat-based adhesives, often referred to as “starch” (FEFCO, n.d.; Fibre Box Association, 2015). Finally, the flat corrugated board sheet comes out of the corrugator and moves to the printing, slotting, die-cutting, folding, and gluing/glue tab processes to become the final shape of a corrugated box.

1.3 Introduction to Life Cycle Assessment (LCA)

With the increased awareness of environmental concerns across the globe, interest in developing methods to assess the environmental impacts of manufactured products has also increased. A Life Cycle Assessment (LCA) is a tool developed to quantify potential environmental impacts and risks of products and systems that could occur during their entire life cycle. International Organization for Standardization (ISO) (2006a) defines

LCA as "compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system." The LCA examines environmental impacts throughout a product's life cycle from raw material extraction, energy acquisition, production and manufacturing, use, reuse, and recycling, all the way through ultimate end-of-life treatments (incineration and landfilling) (Park, 2015; Pennington et al., 2004). LCA studies comply with the international standards established by ISO: ISO 14040-14044. The core standards for LCA are ISO 14040 and 14044, which give framework and guidance for LCAs and information on technical requirements, respectively. ISO 14040 introduces a more general concept and outline of the LCA method (ISO, 2006a), and ISO 14044 provides an operational document for practitioners to conduct LCA studies complying with ISO standards (ISO, 2006b).

An LCA is often used to assist the decision-making process during new product development or during the improvement of an existing product. According to ISO (2006), it could support such activities:

- Spotting opportunities to improve the environmental performance of products in each life cycle stage.
- Offering information that can be the basis for making decisions to decision-makers in industry and policymakers in government.
- Marketing the product with ecolabelling, environmental claims, or environmental product declarations.

1.3.1 Different Phases of the LCA Study

There are four phases in the framework of LCA study: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation (ISO, 2006a). Figure 1.8 gives an idea of the LCA framework in a visualized form.

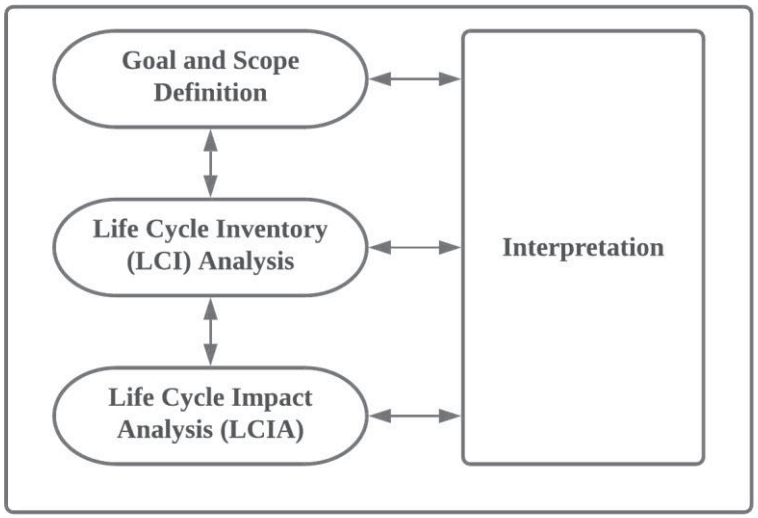

Figure 1.8. Phases of LCA (ISO, 2006a).

Goal and Scope Definition

The first phase of the LCA study is the goal and scope definition phase. At the goal and scope definition stage, the goals and objectives of the study are defined, as well as the functional unit and the system boundaries. The functional unit is defined as the "basis of comparison of product systems" (Curran, 2014) or "a reference to which input and output data are normalized" (Jensen et al., 1997). The system boundary gives the idea of what kind of unit processes will be included in the system (ISO, 2006a). The published standard document for the goal and scope definition phase is ISO 14041 (ISO, 1998).

Life Cycle Inventory (LCI) Analysis

The second stage of the LCA study is the LCI analysis stage. In this phase, related data are collated to build the input/output data inventory for the systems considered in the study (ISO, 2006a). This process requires reporting raw material and energy requirements, emissions to the environment (air, water, and land), pollutant releases, and solid waste generation for the entire life cycle of the product or service of interest (Park, 2015). Usually, the quality of data for life cycle inventory is considered one of the most important parts of the LCA because it collects every input and output of all life cycle stages and significantly affects study results. The lack of LCI for considered products or activities is commonly considered to be the most challenging part of an LCA study.

When collecting LCI data that is not readily available from national or global databases, it is the most time-consuming stage of the LCA study (Guinée et al., 1993).

Three reports from the United States Environmental Protection Agency (EPA) prepared by Battelle & Franklin Associates (1993), Bakst et al. (1995), and US EPA (2006) describe four steps of life cycle inventory analysis: process flow diagram, data collection plan, collection of data, and evaluation and documentation of results.

Process Flow Diagram

A process flow diagram is the visualized form of inputs and outputs for the unit processes within the system boundary from the scope of the study. To efficiently gather data, it is important to break down the system into a set of subsystems (Park, 2015). Subsystems may be grouped when they happen in the same facility. Constructing a firm process flow diagram can assist practitioners clearly and efficiently plan data collection steps.

Data Collection Plan

The next step to build an LCI is the data collection plan. The data collection plan aims to ensure that the accuracy of collected data meets the decision maker's expectations and requirements (US EPA, 2006). The key elements defined with respect to developing a data collection plan are data quality goals, data quality indicators, data sources, and a data collection worksheet.

Data quality goals support balancing the limited time for the study and available resources against the data quality that is required to meet the expectation of decision-makers (US EPA, 2006). Defining data quality can assist practitioners in structuring a better approach to data collection, and it can also play as a data quality performance criterion.

Data quality indicators help practitioners identify whether the quality of data for LCI meets the expectations of decision-makers or not (US EPA, 2006). Practitioners can choose the indicators depending on the type of data collected, but some of the popular examples of data quality indicators are precision, completeness, representativeness, consistency, and reproducibility (US EPA, 2006).

To meet the accuracy and quality required by the goals of the study, identifying data sources and/or types is necessary. Specifying the data source and/or types can reduce time consumption and costs when collecting the data. Some of the examples of data sources are meter readings from equipment, industry data reports, laboratory test results, government reports, journals (LCI or LCA studies), or book references (US EPA, 2006). Collecting the primary data, such as industry data for the manufacturing process, is always the best data source since the production process could be time sensitive due to new technologies released.

The final step for the data collection plan is to prepare a data collection spreadsheet. The spreadsheet needs to cover all systems and/or subsystems that fall into the study's goal. The spreadsheet should be constructed by complying with the eight general decision areas: the purpose of the inventory, system boundaries, geographical scope, types of data used, data collection procedures, data quality measures, computational spreadsheet construction, and presentation of results (US EPA, 2006).

Collection of Data

After all the preparation stages are done, the practitioner executes the collection of data. Data collection can be done in different ways that involve site visits, direct discussion with experts, and literature reviews (US EPA, 2006). The alternative way for this can be to purchase a commercially available LCA software package that contains a database of LCI information from the previous LCI literature (US EPA, 2006).

Evaluation and Documentation of Results

The final stage of LCI analysis is the evaluation and documentation of results. The entire outcome of data collection, including material and energy inputs and emissions to the environment, will be documented and organized by tables in this stage. The methodologies used to conduct data collection and assumptions made will also be documented in this stage. The way LCI analysis results are presented can be different depending on the purposes for the study and its audience.

Life Cycle Impact Assessment (LCIA)

When the LCI analysis is done, LCIA is the next phase of the LCA study. LCIA is an evaluating process of the environmental impacts generated by the investigated products or systems by using the LCI results (ISO, 2000a). It consists of defining the impact categories chosen, data classification, characterization, and valuation/weighting of the results (Jensen et al., 1997). There are two modeling approaches for LCIA: midpoint impact assessment modeling and endpoint impact assessment modeling. Midpoint impact assessment modeling reveals the potential stressors at a midpoint in the cause-effect chain (US EPA, 2006). The midpoint approach renders the LCI results in real phenomena like climate change, acidification, and ozone depletion (Sharaai et al., 2010). The LCIA methodologies based on the midpoint approach are CML 2001, TRACI, and EDIP 97. The endpoint modeling is defined as "the elements inside the impact pathway that consists of an independent value for society" (Heijungs et al., 2008). The endpoint approach converts the results of LCI into impact indicators based on the area of protection: for instance, human health, natural resources, and environmental quality (Bare & Gloria, 2008). Some examples of a methodology based on the endpoint are Eco-Indicator 95, EPS 2000, and LIME 2003 (Sharaai et al., 2010). Midpoint modeling is generally known as a more comprehensive approach and a less complex model than endpoint modeling because it minimizes the amount of forecasting, assumptions, and safety margins (Bare & Gloria, 2008).

Life Cycle Interpretation

The life cycle interpretation phase is the last stage of the LCA study. In this stage, the results or findings from LCI analysis and LCIA are both considered (ISO, 2000b). The interpretation phase derives conclusions and recommendations from the results and findings within the defined goal and scope (ISO, 2000b). The objective of the life cycle interpretation section is to provide a readily understandable, complete, and consistent presentation of the results to the audience (ISO, 2006a).

1.3.2 LCA studies for wood pallets

Over the past decades, many LCA studies on the environmental impacts of wood pallets have been conducted. Historically, researchers have focused on providing life cycle

inventory (LCI) data on different pallet life cycle stages and also on comparing pallets produced from different materials.

Lee & Xu (2004) investigated the environmental impacts of wood pallet and plastic bulk transit packaging systems using a simplified LCA method with the geographical scope of New Zealand. The functional unit was one unit of pallet or plastic packaging system. This study had a cradle to grave approach, but it lacked data on its system boundary of the wood pallet repair process.

Gasol et al. (2008) conducted a life cycle analysis in Spain as representative of the wooden package sector in Europe that compared different reuse intensities of industrial wooden containers. The study was conducted using SimaPro as its environmental impact analysis software and CML Leiden 2000 as its life cycle impact assessment (LCIA) method, presenting the midpoint impact data. Four cases were compared in this study: high reuse pallet, low reuse pallet, low reuse spool, and null reuse spool. This study had a 'cradle-to-grave' approach for its system boundary, which includes raw material extraction, manufacturing, transportation, use, maintenance, and final disposal. The functional unit for wood pallets and wood spools were chosen to satisfy the transport necessity for 1,000 tons by road of a product whose density is 1 t/m^3 with wooden pallets in Spain and by road of electrical cable or optics fiber with wooden spools in Spain, respectively. This study provided two separate results. The first result of the study was life cycle inventory data for the wood pallet and spool maintenance stage. The other result of the study was the comparative life cycle assessment results of the study cases that showed that the system with higher reuse intensity had lower energy and wood (raw material) consumption levels. The wood consumption levels turned out to be the main factor determining the environmental impact of raw material extraction and the process chain stage. The study concluded that the highly reusable and recyclable pallet should be encouraged in order to reduce the demand for natural resources, which significantly contributes to the environmental burdens.

Ng et al. (2014) conducted a comparative life cycle analysis on recycled wood waste (technical wood) and virgin softwood used for building wood pallets focusing on their carbon footprint. The geographical scope was limited to Singapore. The functional unit for this study was a pallet system of standard size (1200 mm x 1000 mm). Unlike the

other studies reviewed, the system boundary of this study only covered 'cradle to gate', which includes raw material extraction, manufacturing, and usage. Because of the variability and limitation of data, the maintenance and storage processes of the pallet and the weight of the unit load were excluded from the system boundary. This study found that the technical wood (referred to as recycled wood waste) pallet has lower carbon emissions than a virgin softwood pallet. The main contributors to this result were the low percentage of unrecoverable timber waste due to engineering scrap created during the technical wood pallet production and the avoided impact generated from the technical wood pallet for not harvesting 0.067m^3 of pine tree required to produce virgin softwood pallet for a baseline of 1 year.

Carrano et al. (2014) investigated the detailed greenhouse gas (GHG) emission impact of three wood pallet types' (expendable, stringer, and block) life cycle phases under specific assumptions to support decision making when companies choose pallet designs or pallet logistic systems by providing the list of the areas potentially improved for the environment. The scope investigated in this life cycle assessment study was cradle to grave. The data for this study were collected from various primary sources, such as pallet manufacturers located in the northeastern and southeastern United States. The quantifying process of the carbon footprint was done by custom processes built using LCA software SimaPro. The results showed that the dominant contributors to the environmental impact of premanufacturing materials, manufacturing, transportation, refurbishing, and end-of-life (EOL) phase were wood use, heat treatment, tare weight of the pallet, transportation type, transportation, and disposal, respectively. This study listed recommendations of potential actions that could be done to improve the sustainability of the wood pallets for every stakeholder and presented a detailed carbon footprint analysis for each phase to support decision making.

Carrano et al. (2015) also conducted an environmental analysis based on the carbon emission impact perspective of three predominant pallet management strategies in the United States: single-use expendable, reusable buy/sell, and reusable leased pool. The study developed functions to calculate each phase's carbon emission from the Global Warming Potential midpoint data. The study found that loading and handling conditions for pallets greatly affect the number of useful trips which directly impacts the carbon

emission level of the whole life cycle. The EOL conditions also play a notable role. The authors suggest logisticians to use a combination of management strategies to minimize the environmental impact caused by carbon emissions. However, similar to the author's previous study, this study only focused on the carbon equivalent emissions, and there could be room for an extended study to assess environmental pallet management strategies using more impact categories to provide a more holistic view.

Bengtsson & Logie (2015) looked at the environmental impacts of different material use (softwood, hardwood, and plastic) in pooled pallet systems, and their key market competitors: simple/one-way softwood or cardboard pallet manufactured in either China or Australia. The pallet dimensions were chosen as Australian Standard pallet size (1165 mm x 1165 mm) and 1200 mm x 1000 mm for China. The 1,000 customer trips were picked as the functional unit of this study to compare the environmental impacts of different pallet systems. The life cycle inventory of this study was modeled using the LCA software SimaPro and the LCIA method of ReCiPe. The results presented showed that using a pooled wood pallet system with regular maintenance produces the least environmental impacts and more economic benefits than the other systems compared in this study since the closed-loop and maintenance allow pallets to perform a greater number of trips. The study also found that single-use pallets perform better environmentally when the situation is an open loop that cannot guarantee the return of pallets to the repair facility. Their paper had assumptions in the number of trips available for each pallet and the durability difference between hardwood and softwood pallets. Hardwood is 50% more durable than softwood, based on their experiences, which could have significantly affected the results of their study.

Park et al. (2018) developed life cycle inventory data for the repair process specifically for the Grocery Manufacturers Association (GMA), stringer class, wood pallets. The primary data was collected from seven different pallet repair sites located in the United States. The developed inventory showed the operation of machinery mostlye emitted GHG during the repair processes, and that steel nails were the greatest contributor among the material inputs. The study found that the massive GHG offset occurred by the by-products produced during the repair process, such as dismantled lumbers or steel nails, gave GHG credits for the process.

Kočí (2019) compared the environmental impacts of EUR-wood pallets, virgin plastic pallets, and recycled plastic pallets in the Czech Republic. Like other pallet LCA studies, the scope was cradle to grave. This study found that the weight of the pallet increases the overall weight of transported cargo, which is reflected in the overall environmental impact of the shipment. The study concluded with two different perspectives for interpreting results: pallet end-of-life options and the weight of wood pallets. The interpretation from the end of life perspective showed that the wood pallets, either with or without incineration and energy recovery taking place at the end of life stage, are more environmentally friendly than plastic pallets, but wood pallets without the incineration energy recovery stage have more environmental impact than the recycled material plastic pallets. The use of different wood species, including pine and spruce, for wood pallet material changed the weight of wood pallets, resulting in different amounts of environmental impacts. This paper is the first research attempt to analyze from the LCA perspective how the weight reduction of tertiary packaging could have a significant environmental impact on the distribution packaging system.

Anil et al. in 2020, recently conducted a comprehensive life cycle assessment study to provide convincing environmental impact results of wood and plastic pallets. They implemented two functional units in one study, a single trip of the pallet and 100,000 trips of the pallets. This study focused on the different treatment processes of wood pallets as a significant environmental contributor. They provided a detailed life cycle inventory of wood pallets from the raw material extraction process to manufacturing. The results recommended that wood pallets are more environmentally friendly than plastic pallets and that conventional and radiofrequency heat treatment for wood pallets is the more sustainable option compared to methyl bromide fumigation treatment.

1.3.3 LCA Studies of Corrugated Boxes

Since corrugated boards are the most commonly used packaging material, extensive pertinent prior studies have addressed the environmental impact of corrugated boxes using the life cycle assessment method.

Many existing studies from different industries have evaluated the environmental performance of corrugated boxes when they are used as secondary packaging or as one of

the components in a whole packaging system (Berlin, 2002; Dimyati & Singgih, 2019; Hospido et al., 2003; S. G. Lee & Xu, 2004; Munasinghe et al., 2017; Salomone et al., 1997; Silvenius et al., 2014; Williams & Wikström, 2011).

Salomone et al. (1997) conducted the LCA case study on certain wine packaging, including primary packaging (glass bottle, cork, and heat-shrink label), secondary packaging (corrugated box), and tertiary packaging (wooden pallet and stretch wrap). The functional unit was a 0.75-liter bottle of wine, and the scope of the study was cradle-to-gate (market use), which started from the agriculture phase of the grape to the market distribution phase of the final product to consumers. The results found that the agricultural phase was the most significant contributor to mineral resource consumption and eutrophication. The results also found that the packaging and distribution phase is highly responsible for climate change, photochemical oxidation, consumption of nonrenewable energy, biomass consumption, ozone depletion, and acidification. However, the results only focused on the responsibility of each phase and did not break down the contribution results into more detailed subsystems that would have shown the contribution of each component.

Several LCA studies were also conducted by employing methods of comparative analysis with corrugated boxes and reusable alternative packaging systems.

Levi et al. (2011), Koskela et al. (2014), and Thorbecke et al. (2019) compared single-use corrugated box packaging systems with reusable plastic container packaging systems. These studies evaluated different materials for the reusable plastic containers; polypropylene (PP) for the first and third study and high-density polyethylene (HDPE) for the second study. Nevertheless, regardless of the materials investigated, studies conducted by Levi et al. (2011) and Koskela et al. (2014) had consistent results showing that the corrugated box packaging system is generally environmentally preferable to the reusable plastic containers. However, study results from Thorbecke et al. (2019) had an unsettled conclusion reporting that either side of the packaging system does not have a clear overall better environmental performance. This was because determining comparative environmental impact results by just counting impact indicators, which showed less or more impact on each packaging type, would require us to assume every impact category is equally important to the environment. Sensitivity analysis on the

increasing use of the reusable plastic containers from all three studies also presented that the number of reuses for the reusable container does not substantially affect the results.

Yi et al. (2017) examined the environmental impact and energy consumption of delivery packaging materials such as corrugated boxes, polypropylene (PP) bags, and packaging tape in China. Raw material extraction phases were excluded from the scope of this study which means this study employed a gate-to-grave perspective. The findings reported that the life cycle of the corrugated box caused much more environmental impact from all four considered impact categories than the PP bag packaging system. The main contributors to global warming potential were the transportation processes and incineration of the corrugated box product. They also found that incineration of corrugated boxes significantly contributes to photochemical oxidation. The energy consumption result found by this study showed a similar trend to the environmental impact result. The life cycle of corrugated boxes consumes about 87% more energy than the life cycle of a PP bag. The production stage, usage stage, and electricity use were found to be the most energy-consuming stage in the life cycle of the corrugated box. Consequently, this study suggested that changing double-wall corrugated boxes to a single wall to reduce the emission from the production stage and recycling could also reduce the raw material consumption of the corrugated box. However, this study did not consider any mechanical properties of double wall and single wall corrugated boxes.

Del Borghi et al. (2020) compared the environmental impact of different material types of crates commonly used for food delivery; reusable plastic crate, non-reusable plastic crate, corrugated box, solid wood crate, medium-density fiberboard (MDF) crate, and particleboard wood crate. The functional unit adopted for this study was one crate of equal size (400 x 600 x 240 mm) and inner volume (50 liters). The results showed that the reusable plastic crate performs best for the environment among all packaging systems considered if the recovery system is well constructed since reusing materials could avoid a large portion of impact coming from manufacturing processes. Since the solid wood crate uses raw material with minimal processing, the solid wood crate was more environmentally friendly than the other single-use packaging scenarios that use processed materials such as corrugated boards, particleboard, MDF, and plastic. The corrugated box was the least environmentally friendly choice due to the high environmental impacts

generated during the paper manufacturing process. In this study, two different sensitivity analyses regarding travel network distances and end-of-life scenarios were conducted to deal with the variability of data. The sensitivity analysis results presented that a higher recycling rate significantly decreases global warming potential emissions.

Zimmermann & Bliklen (2020) recently investigated the carbon footprint and the environmental break-even point of reusable e-commerce shipping packaging types as compared to corresponding single-use alternative packaging systems. They first examined the environmental hotspots of each type of reusable plastic packaging system: polypropylene (PP) box and flexible PP pouch. Then they compared the reusable PP box and reusable flexible PP pouch to an equal volume of corrugated boxes and post-consumer recycled (PCR) low-density polyethylene (LDPE) bags, respectively. According to the comparison results of the reusable PP box and corrugated box, the break-even point for reusable virgin material PP box to produce or emit lesser environmental burdens than the corrugated box was 81 reuse cycles, and if PCR material was used for PP box, the break-even point cycle drops to 32 cycles which is still a high number of cycles. The comparison results of the reusable PP pouch to single use corrugated box and PCR LDPE bag presented that the PCR LDPE bag showed better environmental performance than the corrugated box at the first cycle of use and after eight cycles for the PCR LDPE bag. Since corrugated boxes had higher weight and PCR LDPE bag had less weight than reusable PP pouch, the authors stated that the weight of packaging material was significantly affected due to the higher impact generated from the production and transportation.

Scholars in the past also examined the environmental hotspots of the corrugated box itself. Ongmongkolkul et al. in 2001, conducted a detailed LCA study on the life cycle of the corrugated box produced from virgin pulp and recycled corrugated materials in Thailand. The study analyzed energy use and five different midpoint impact categories, including global warming, acidification, eutrophication, photochemical ozone formation, and solid waste generation created. The results from this study showed that landfilling at the end-of-life phase was the primary contributor to the analyzed five midpoint impact categories. The drying process of the corrugated board production process was the main energy-consuming phase, and the box production process generated the largest amount of solid

waste during the whole life cycle. The authors also suggested the potential environmental impact reduction points. They suggested that increasing the corrugated boxes' recycling rate and improving landfill gas collection and treatment system would significantly reduce emissions from landfills. Authors stated that re-designing the corrugated boxes by lowering their weight could reduce energy consumption by 40%-60% during the production stage which could reduce the environmental emissions on global warming potential by 20% and acidification by 10%.

Li et al. (2014) examined the environmental strengths and weaknesses of the conventional corrugated boxes manufactured in China. The impact assessment of this paper was performed for eleven midpoint and endpoint impact categories, including carcinogens, respiratory organics, respiratory inorganics, climate change, radiation, ozone layer, ecotoxicity, acidification/eutrophication, land use, minerals consumption, and fossil fuels consumption. The most considerable impacts generated from the life cycle of the corrugated box were respiratory inorganics, climate change, and acidification/eutrophication. According to the results of this study, the corrugated box production phase was the main contributor to environmental impacts due to the excessive amount of fuel consumption and air emission/wastewater pollution.

Verma et al. (2019) investigated the environmental impacts of the life cycle of one corrugated box manufactured in the semi-skilled corrugated industry in India. The system boundary for this study was a gate-to-gate scenario and only covered the manufacturing phase and associated transportation processes. Four different impact indicators applied to analyze the environmental burdens of the corrugated box manufacturing process were as follows: acidification, global warming potential, ozone depletion, and human toxicity (cancer). Researchers found that methane emissions from landfilling contribute most to the global warming potential category, and ammonia emissions from landfilling affect acidification the most. They concluded that landfilling and electricity consumption during the corrugated box manufacturing phase were the main contributors to environmental impacts, and the rate of landfilling was over 60% which makes it become a significant contributor.

Although the environmental impacts of wood pallets and corrugated board boxes have been studied by previous researchers from many different perspectives using the LCA

method, the potential environmental benefits from optimizing the performance of unit loads utilizing the interaction between the two main components has not yet been discovered. Investigating the environmental impact of increasing the stiffness of the wood pallet top deck board for unit loads carrying corrugated boxes will help to improve the packaging industry's understanding of whether this unit load design optimization strategy not only reduces the use of corrugated board materials and cost, but also generates the reduction of the environmental footprint of the overall shipping system using the unit loads.

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2 Chapter 2: Investigation of the Effect of Pallet Top-Deck Stiffness on Corrugated Box Compression Strength as a Function of Multiple Unit Load Design Variables

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2.1 Abstract

Unit loads consisting of a pallet, packages, and a product securement system are the dominant way of shipping products across the United States. The most common packaging types used in unit loads are corrugated boxes. Due to the great stresses created during unit load stacking, accurately predicting the compression strength of corrugated boxes is critical to preventing unit load failure. Although many variables affect the compression strength of corrugated boxes, re-cently, it was found that changing the pallet's top deck stiffness can significantly affect compression strength. However, there is still a lack of understanding of how these different factors influence this phenomenon. This study investigated the effect of pallet's top-deck stiffness on corrugated box compression strength as a function of initial top deck thickness, pallet wood species, box size, and board grade. The amount of increase in top deck thickness needed to lower the board grade of corrugated boxes by one level from the initial unit load scenario was determined using PDS™. The benefits of increasing top deck thickness diminish as the initial top deck thickness increases due to less severe pallet deflection from the start. The benefits were more pronounced as higher board grade boxes were initially used, and as smaller-sized boxes were used due to the heavier weights of these unit loads. Therefore, supposing that a company uses lower stiffness pallets or heavy corrugated boxes for their unit loads, this study suggests that they will find more opportunities to optimize their unit loads by increasing their pallet's top deck thickness.

Keywords: corrugated box; compression strength; pallet; unit load; unit load optimization

2.2 Introduction

Historically, the distribution packaging industry has adapted the method of unitizing single, multiple, or bulk products on a solid platform to make the handling, storing, and transporting of these products easier (White & Hamner, 2005). This arrangement is called a unit load. In today's supply chains, 80% of products are moved in unit load form (Raballand & Aldaz-Carroll, 2007). The most common base platform for unit loads is a pallet. Pallets can be made of different materials such as wood, plastic, paper, or metal.

Among these materials, wood is by far the most commonly used to manufacture pallets. Wood is the material of choice for over 90% of companies that use pallets in their supply chains in the United States (McCrea, 2020). Furthermore, approximately 804 million new and recycled wood pallets were manufactured in 2016 (Gerber et al., 2020). Just as wood pallets have become one of the essential elements of a unit load, corrugated boxes also play a crucial role. Corrugated boxes are the most used primary and secondary packaging; in fact, 72% of unit loads are built using corrugated boxes (McCrea, 2020).

When designing a unit load, accurately predicting corrugated box compression strength is crucial to avoid package failure from the vertical compression forces during distribution and storage. Therefore, numerous studies have investigated the factors that affect the compression strength of corrugated boxes, including material properties (Almanza et al., 1993; Frank, 2014; Kawanishi, 1989; Kellicutt & Landt, 1958; McKee et al., 1963; Popil et al., 2006), manufacturing methods (Han & Park, 2007; Jinkarn et al., 2006; Kellicutt & Landt, 1958; Kwak, 2010; Singh et al., 2009; Surber & Catlin, 1982; Urbanik & Frank, 2006), environmental condition factors (Frank, 2014; Kellicutt & Landt, 1958; Urbanik & Frank, 2006; Whitsitt & McKee, 1972), and the palletization factor (Baker, 2016; DiSalvo, 1999; Godshall, 1968; Kellicut, 1963; Marcondes, 1992; Phanthanousy, 2017; Quesenberry et al., 2020; Singh et al., 2011; Yoo, 2011).

Wood pallet characteristics, such as pallet gaps and pallet overhang, have been included among the main palletization factors that affect box compression strength. In relatively recent years, researchers have endeavored to correlate pallet top-deck stiffness to corrugated box compression strength. Baker (2016) and Phanthanousy (2017) examined the relationships between the differences in stress concentrations and box compression strength. However, their studies were inconclusive. Phanthanousy (2017) found that the stiffness of the pallet's top deck has no notable effect on box compression strength when the wood pallet is designed with deck board gaps.

Meanwhile, Baker (2016) found that pallet top-deck stiffness significantly affects box compression strength when the wood pallet is designed with no deck board gaps. Their studies only evaluated situations in which all corners of the boxes were symmetrically supported. However, in many cases, the top deck board of a wood pallet deforms by the weight of the top load and creates asymmetric support conditions for the loaded products.

Baker (2016) highlighted that asymmetrically supported corrugated boxes are a prevalent condition in most unit loads, and his research found that asymmetric support can decrease corrugated box compression strength by as much as 15%.

In 2020, Quesenberry et al. (2020) further investigated the effect of wood pallet top-deck stiffness on corrugated box compression strength when box corners are asymmetrically supported. They concluded that a stiffer top deck board could increase the compression strength of asymmetrically supported corrugated boxes up to 37% when the unit loads are double-stacked on the floor (Quesenberry, 2020). They also discovered that the effect of pallet top-deck stiffness on box compression strength could be utilized to lower the cost of a unit load by decreasing the required board grade of corrugated boxes and increasing the pallet's top deck thickness. However, the experimental design utilized by Quesenberry only focused on a limited number of variables. Furthermore, the pallet design utilized for his experimental unit load consisted of a single wood species and singular moisture content.

Additionally, the corrugated boxes were made of a single board grade, two flute sizes, and two box sizes. In practice, many wood species with varying moisture content are available for pallet manufacturing; meanwhile, corrugated boxes are produced in multiple board grades and sizes. Nevertheless, there is an absence of studies investigating how these variations may change the effect of top deck stiffness on corrugated box compression strength.

Therefore, the objective of this current paper is to investigate the effect of pallet top deck stiffness on the compression strength of asymmetrically supported corrugated boxes as a function of currently under-studied variables, including initial top deck thickness, pallet wood species, box size, and board grade.

2.3 Materials and Methods

This study consisted of two main sections: validation of the analytical pallet design software and unit load scenario analysis.

2.3.1 Software Validation

The commercially available pallet design software Pallet Design System™ (PDS™) v. 6.2, created by NWPCA (NationalWooden Pallet & Container Association, Alexandria, VA, USA) was utilized to replace numerous physical experiments in this study. The box performance data predicted by PDS™ and that Quesenberry et al. (2020) found were compared to confirm that the software reproduced the results from the experiment.

2.3.1.1 Corrugated Box Description for Validation

The same designs of corrugated boxes used by Quesenberry et al. (2020) were used to build the unit load model in PDS™for predictive software validation. Specified parameters from Quesenberry et al. (2020) included: Regular Slotted Container (RSC) style with two different external dimensions (length x width x height) 406.4 mm x 247.7 mm x 254 mm and 609.6 mm x 247.7 mm x 254 mm. Unit loads were built with four layers of boxes, and the configuration of boxes was either 3 boxes x 4 boxes (length x width) or 2 boxes x 4 boxes. Both sizes of boxes were built with nominal 0.57 kg/mm Edge Crush Test (ECT) value B-flute and C-flute corrugated board.

2.3.1.2 Pallet Description for Validation

Quesenberry et al. (2020) simulated a 1219.2 mm x 1016 mm GMA™ (Grocery Manufacturers Association) style pallet by using a custom-built, quarter-section pallet for testing purposes. For software validation, a full-sized 1219.2 mm x 1016 mm stringer class, double face, non-reversible, partial four-way, unidirectional bottom, flush, GMA™ style pallet was modeled in PDS™ (see Figure 2.1). The pallet consisted of three stringers, seven top deck boards, five bottom deck boards, and two fasteners per joint. The stringers were 1219.2 mm long, 31.8 mm wide, and 88.9 mm high. The top and bottom deck boards were 1016 mm long and 88.9 mm wide. The four top deck board thicknesses studied were: 9.5 mm, 12.7 mm, 15.9 mm, and 19.1 mm. All top deck boards were equally spaced 99.6 mm apart. Lead bottom deck boards were spaced 292.1 mm away from the interior bottom deck boards, and the interior bottom deck boards were spaced 95.3 mm apart. Number 1 & better (premium & better), kiln-dried, Spruce–Pine–Fir (SPF) lumber was used for all pallet components.

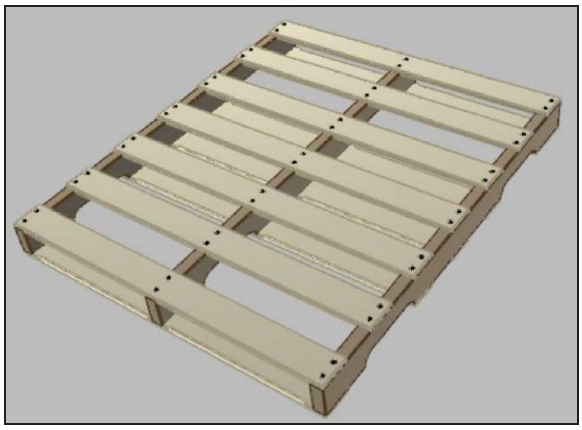

Figure 2.1. Picture of GMA pallet used for software validation (image generated using PDS™).

2.3.1.3 Comparison of Box Load Factor and Box Compression Strength Factor

During software validation, the box load factors computed by PDS™ and the box compression strength factor derived from the thesis of Quesenberry (2020) were compared. The box load factor is the ratio of the weights on worst loaded box edges to the load if it were evenly distributed. Meanwhile, the box compression strength factor is a new term developed by the authors and is defined as the ratio of the box compression strength when box corners are symmetrically supported on rigid supports to the box compression strength when its corners are asymmetrically supported on an actual pallet. Both the box load factor and the box compression strength factor ultimately provide information about the compression performance of the corrugated box.

Process of Computing Box Load Factor

Box load factors were computed using PDS™ following the steps described below.

Step 1: Built a unit load in PDS™ using boxes and pallets previously described in Sections 2.1.1. and 2.1.2.

Step 2: Set the top deck board thickness to the lowest level (9.5 mm).

Step 3: Set the weight in the box to the load that will just fail the boxes (box safety factor of one) when the support condition is a single floor stack.

Step 4: Report current box load factor when support condition is single floor stack.

Step 5: Increased the top deck board thickness to the following levels (12.7 mm, 15.9 mm, and 19.1 mm).

Step 6: Repeat steps 3 and 4 for each level of top deck board thickness.

Step 7: Repeat the process for two flute sizes (B and C flute) and two box sizes.

Process of Calculating Box Compression Strength Factor

The box compression strength factor from Quesenberry's study was calculated using Equation 2.1:

$$CSF = \frac{SCS_{avg}}{ACS_{avg}}$$

Equation 2.1. Compression Strength Factor Equation

Where:

CSF = Box compression strength factor.

SCSavg = Average box compression strength when box corners are symmetrically supported on a rigid platform.

ACSavg = Average box compression strength when box corners are asymmetrically supported on the actual pallet.

The unit load scenarios used to calculate the box compression strength factors were varied by two flute sizes, two box sizes, and four thickness levels.

Statistical Analysis

The independent t-test was conducted to see whether the difference between box load factors from PDS™ and box compression strength factors from the experiment were statistically significant or not. To confirm the normality assumption of the independent t-test, we also ran the Shapiro–Wilk test for each group separately. The similarities between the box performance data from PDS™ and the experiment were also assessed using the Pear-son correlation coefficient. The Pearson correlation coefficient is a way to investigate linear dependence between two variables. The measured correlation coefficient (r) ranges be-tween −1 and +1. When the r-value is −1, it indicates a strong negative correlation, while +1 indicates a strong positive correlation, and 0 means no relation. Both statistical analyses were conducted at a significance level of 0.05. The analyses were done using SAS JMP Pro 15® software (SAS Enterprises, Raleigh, NC, USA).

2.3.2 Unit Load Scenario Analysis

The concept of a unit load cost optimization method that allows for corrugated boxes with decreased board grades by increasing the pallet's top deck thickness was adopted from Quesenberry et al. (2020) to modify each unit load scenario. In other words, the analysis was done by determining how much the top deck thickness needed to increase to lower the corrugated board grade by one level from the initial unit load scenario's specific deck board thickness and board grade. A total of 234 unit load scenarios were designed with varying factors for investigation.

2.3.2.1 Corrugated Box Description for Unit Load Scenario Analysis

Three sizes of RSC-style corrugated boxes were investigated to explore the effect of different box sizes. Three box sizes were chosen that would cover the entire top surface of the 1219.2 mm × 1016 mm pallet and create asymmetrically supported corners. The external dimensions were 203.2 mm × 304.8 mm × 254 mm (small box), 406.4 mm × 254 mm × 254 mm (medium box), and 609.6 mm × 337.8 mm × 254 mm (large box). The boxes were organized in 4 × 5, 3 × 4, and 2 × 3 arrays for small, medium, and large boxes, respectively. Four layers of boxes were used for each unit load. Unit load configurations using the different box sizes are depicted in Figure 2.2. The boxes were built with two different flute sizes: single-wall C-flute and double-wall BC-flute. The C-flute and BC-flute corrugated boards were made of commonly manufactured board grades for each flute size. C-flute boards were modeled with nominal 0.52 kg/mm., 0.57 kg/mm, 0.71 kg/mm, and 0.79 kg/mm ECT. BC-flute boards were modeled with nominal 0.86 kg/mm, 0.91 kg/mm, 1.09 kg/mm, and 1.27 kg/mm ECT.

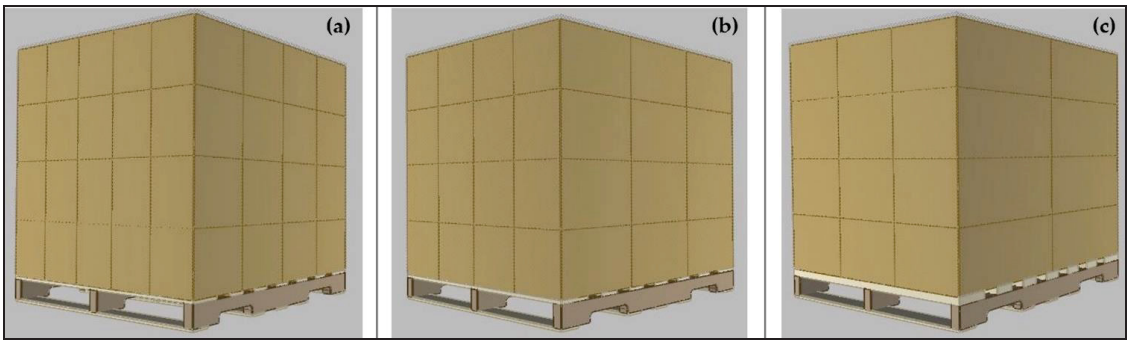

Figure 2.2. Image of investigated unit load configurations (image generated using PDS™). (a) Unit load with small boxes, (b) unit load with medium boxes, and (c) unit load with large boxes.

2.3.2.2 Pallet Description for Unit Load Scenario Analysis

For the unit load scenario analysis, the most common size of GMA™ style wood pallet was used. The 1219.2 mm × 1016 mm GMA™ style stringer class wooden pallet is the most commonly used pallet design in North America (Bejune, 2001; Clarke et al., 2005). The specifications were 1219.2 mm × 1016 mm, stringer class, double face, non-reversible, partial four-way, unidirectional bottom, flush, GMA™ style pallet (see Figure 2.3). The pallet design had three stringers, two lead top deck boards, five interior top deck boards, five bottom deck boards, two fasteners per joint on the interior top deck boards and for all bottom deck board connections, and three fasteners per joint on the lead top deck boards. The pallet design utilized for the unit load scenario analysis (Figure 2.3) had 50.8 mm wider lead top deck boards than the pallet design used for the software validation process (Figure 1). The spacing between top deck boards has also changed accordingly. The stringers were 1219.2 mm long, 31.8 mm wide, and 88.9 mm high. The interior top deck boards and bottom deck boards were 1016 mm long and 88.9 mm wide. The lead top deck boards were 1016 mm long and 139.7 mm wide. The bottom deck boards were 9.5 mm thick. All top deck boards were spaced 82.6 mm apart. The lead bottom deck boards were spaced 292.1 mm apart from interior bottom deck boards, and interior bottom deck boards were spaced 95.3 mm apart from each other. Number 1 & better (premium & better) grade lumber was used for all pallet components.

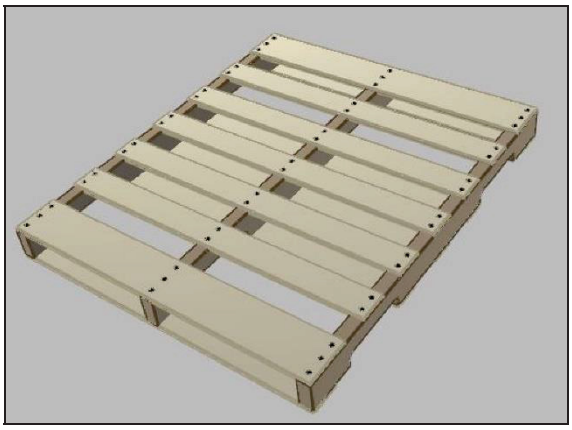

Figure 2.3. Picture of GMA pallet used for analysis (image generated using PDS™).

Initial top deck thicknesses were varied by four levels to explore which changes in deck board thicknesses would be required to reduce by one level the initial board grade specified for the corrugated boxes. The investigated initial top deck thickness levels were 9.5 mm, 12.7 mm, 15.9 mm, and 19.1 mm. However, unit load scenarios built with kiln-dried southern yellow pine (KD SYP) pallets were designed with 11.1 mm top deck boards, and this thickness was increased to 17.5 mm for the optimized design. This limitation was due to the availability of raw material sizes; only the 11.1 mm and 17.5 mm dimensions could be manufactured effectively.

Wood species used for pallet construction were also varied. The wood species commonly used for pallet construction in the southeastern United States were selected. Select-ed wood materials were: green, high-density hardwood (Grn HD HW); green, low-density hardwood (Grn LD HW); green, southern yellow pine (Grn SYP); and kiln-dried, southern yellow pine (KD SYP). Green lumber contained 25% or greater moisture content, and kiln-dried lumber had a maximum of 19% moisture content.

2.3.2.3 Variable Factors

Several factors of the unit load were varied to identify the characteristics that could change the effect of the pallet's top deck board stiffness on box compression strength. The factors evaluated were initial top deck board thickness, pallet wood species, box size, and corrugated board grade. The variable factors that relate to pallets are listed in Table 2.1, and Table 2.2 contains the variable factors relating to the boxes.

Table 2.1. Summary table of variable factors related to pallets.

Pallet wood species	Green high-density hardwood Green low-density hardwood Green southern yellow pine Kiln-dried southern yellow pine
Initial top deck thickness for green lumber	9.5 mm 12.7 mm 15.9 mm 19.1 mm
Fixed range for KD SYP lumber thickness	11.1 mm to 17.5 mm

Table 2.1. Summary table of variable factors related to corrugated boxes.

Box size (mm)	Flute size	ECT Range (kg/mm)
Small (203.2 × 304.8 × 254)	C	0.57 to 0.52
Medium (406.4 × 254 × 254)		0.71 to 0.57
		0.79 to 0.71
Large (609.6 × 337.8 × 254)	BC	0.91 to 0.86
		1.09 to 0.91
		1.27 to 1.09

2.3.2.4 Analysis Method

Measurement of Top Deck Thickness Increase

The unit load cost optimization method adopted from Quesenberry et al. (2020) was investigated by varying the factors introduced in Section 2.3.2.3. The change in top deck thickness required to reduce by one level the corrugated board grade used, without down-grading box performance, was measured. This analysis was done with the unit load in the double floor stacked condition. A box safety factor of 3 was selected for the unit load design to comply with the requirements of the ISTA 3E testing standard (International Safe Transit Association, 2017).

Required steps in the analysis were as follows:

Step 1: Construct the unit load in PDS™.

Step 2: Set pallet material as one of the listed wood species (i.e., green high-density hardwood).

Step 3: Set the top deck board as the lowest initial top deck board thickness (9.5 mm). In the case of KD SYP, always set the initial top deck thickness as 11.1 mm.

Step 4: Set corrugated boxes as the higher ECT values in the selected range of board grade (i.e., Choose 0.57 kg/mm if the range was decreasing from 0.57 kg/mm to 0.52 kg/mm).

Step 5: Determine the weight of the box that works to create a box safety factor of three for the double floor stacking condition.

Step 6: Create a new unit load with the corrugated boxes made of lower ECT value from the selected range of corrugated board grade and apply the weight determined in step 5 (i.e., Select 0.52 kg/mm if the range was 0.57 kg/mm to 0.52 kg/mm).

Step 7: Continuously increase the top deck thickness by 1.6 mm until the unit load again reaches the safety factor of three for safe operation. In the case of KD SYP, always increase the top deck thickness to 17.5 mm.

Step 8: Report the total increase in the top deck board thickness required to achieve the required safety factor of three.

Step 9: Repeat step 1 to step 8 after changing the pallet wood species.

Step 10: Repeat from step 1 to step 9 after increasing the initial top deck stiffness level.

Step 11: Repeat from step 1 to step 10 after changing the range of board grade (i.e., changing from a range of 0.57—0.52 kg/mm to a range of 0.71—0.57 kg/mm).

Step 12: Repeat from step 1 to step 11 after changing the size of corrugated boxes (i.e., changing from a small to a medium size box).

Unit Load Scenario Classification System

The amount that the top deck thickness increased was categorized as one of three grades to make it easier to identify which scenarios had smaller or larger increases in top deck thickness: less than 12.7 mm (grade 1), 12.7 mm to 25.4 mm (grade 2), and beyond 25.4 mm increase (grade 3). For better visualization, a color-coding system was also applied; green for grade 1, yellow for grade 2, and red for grade 3. Grade 1 scenarios were considered as cases with high potential to apply the unit load optimization process. Grade

2 scenarios were considered cases that may be possible to apply the optimization method depending on the manufacturer's circumstances. Because pallets made of deck boards thicker than 25.4 mm are unprecedented; grade 3 scenarios were considered unrealistic unit load designs.

2.4 Results and Discussion

2.4.1 Software Validation Results

Measurement of the box load factors and box compression strength factors on varied top deck thicknesses, box sizes, and flute sizes are presented in Table 2.3. The comparison of box load factors and box compression strength factors is plotted in Figure 2.4. It was observed that PDS™ tends to overestimate the effect of top deck stiffness when compared to the experiment results. However, the independent t-test showed that the difference between PDS™ and the experiment was not statistically significant ($t(25) = -0.85$, *p-value* = 0.40). The Shapiro-Wilk test confirmed that the normality assumptions were met (PDS: W = 0.927, *p-value* = 0.216; Quesenberry: W = 0.919, *p-value* = 0.160). Furthermore, the Pearson correlation coefficient revealed a strong positive correlation, r = 0.911 (*p-value* < 0.0001), between box load factors from PDS™ and box compression strength factors from experiment results. In other words, the PDS™ and Quesenberry's (2019) experiments had a similar pattern.

Table 2.3. Summary table of box load and compression strength factors.

	Box Load and Compression Strength Factor							
	Small C-Flute Box		**Large C-Flute Box**		**Small B-Flute Box**		**Large B-Flute Box**	
Topdeck Thickness (mm)	PDS	Experiment	PDS	Experiment	PDS	Experiment	PDS	Experiment
9.5	1.366	1.362	1.332	1.363	1.375	1.513	1.360	1.334
12.7	1.268	1.145	1.225	1.152	1.307	1.320	1.258	1.172
15.9	1.187	1.090	1.153	1.116	1.222	1.298	1.179	1.117
19.1	1.136	1.005	1.109	1.075	1.165	1.105	1.129	1.022

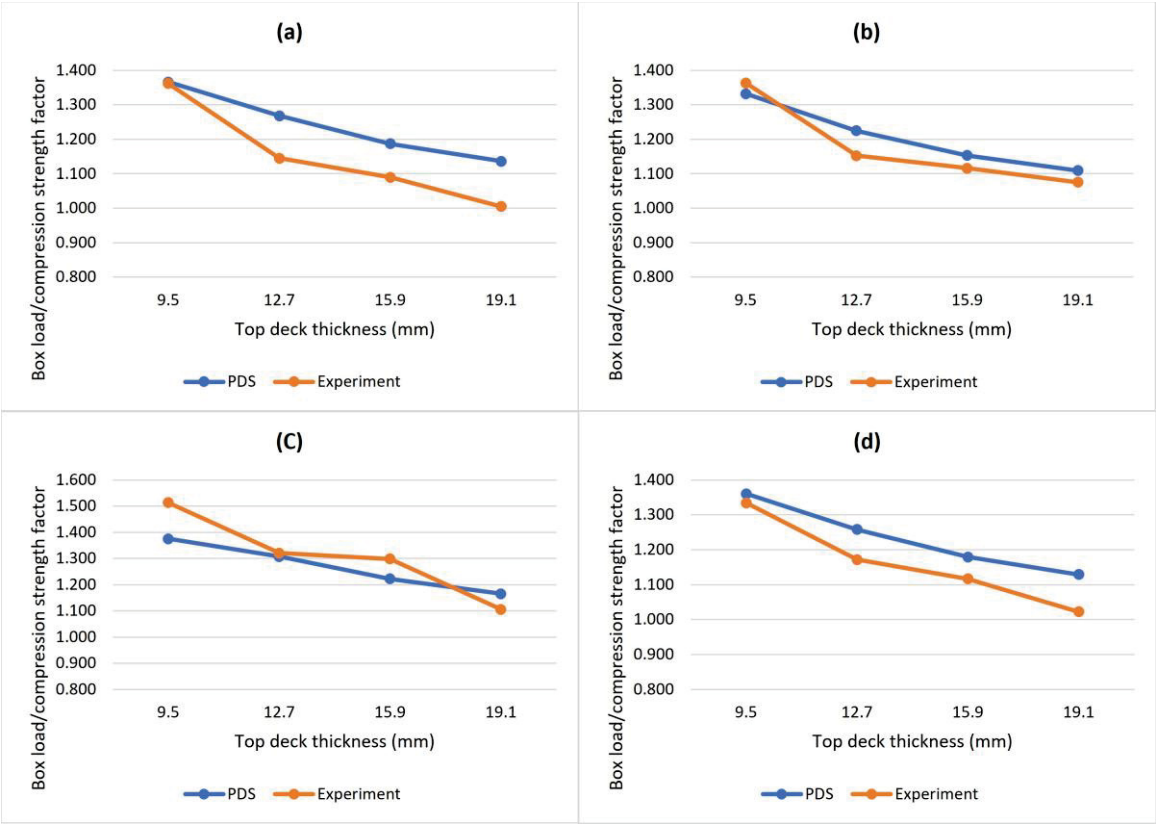

Figure 2.4. Comparison of box load factors and box compression strength factors of each type of boxes in response to pallet top-deck thickness. (a) Small C-flute box scenarios, (b) shows large C-flute box scenarios, (c) shows small B-flute box scenarios, and (d) shows large B-flute box scenarios.

2.4.2 Unit Load Scenario Analysis Results

Table 2.4 and Table 2.5 report the amount of top deck board thickness increase required to reduce the corrugated board grade by one level as a function of starting top deck thickness, wood species, initial board grade, and box sizes for the unit loads consisting of C-flute boxes and BC-flute boxes, respectively. A streamlined grading system has been applied, as described in Section 2.3.2.4, for better visualization and identification of the level of top deck thickness increase. The top deck thickness increase for grade 3 scenarios was re-ported as N/A (not applicable) because adding an extra inch of thickness to a pallet deck board is highly cost-prohibitive.

Table 2.4. The amount of top deck board thickness required to optimize unit loads consisting of C-flute boxes.

			Amount of top deck thickness increase (mm)								
		C-Flute	0.57 – 0.52 kg/mm ECT			0.71 – 0.57 kg/mm ECT			0.79 – 0.71 kg/mm ECT		
		Initial top deck thickness (mm)	Grn HD HW	Grn LD HW	Grn SYP	Grn HD HW	Grn LD HW	Grn SYP	Grn HD HW	Grn LD HW	Grn SYP
C-Flute	Small	9.5	3.2	3.2	3.2	8	6.4	8	3.2	3.2	3.2
		12.7	4.8	4.8	6.4	N/A	N/A	N/A	4.8	3.2	4.8
		15.9	15.9	9.5	N/A	N/A	N/A	N/A	9.5	6.4	9.5
		19.1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Medium	9.5	4.8	4.8	4.8	22.2	22.2	12.7	3.2	3.2	3.2
		12.7	12.7	8	8	N/A	N/A	N/A	8	6.4	4.8
		15.9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	15.9
		19.1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Large	9.5	8	9.5	9.5	N/A	N/A	N/A	9.5	11.1	11.1
		12.7	N/A	19.1	19.1	N/A	N/A	N/A	12.7	12.7	12.7
		15.9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		19.1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Grade 1: less than 12.7 mm (green), Grade 2: 12.7 mm to 25.4 mm (yellow), Grade 3: beyond 25.4 mm increase (red).

Note: Grn HD HW: green high-density hardwood, Grn LD HW: green low-density hardwood, Grn SYP: green southern yellow pine.

Table 2.5. The amount of top deck board thickness required to optimize unit loads consisting of BC-flute boxes.

			Amount of top deck thickness increase (mm)								
			0.91 – 0.86 kg/mm ECT			1.09 – 0.91 kg/mm ECT			1.27 – 1.09 kg/mm ECT		
		Initial top deck thickness (mm)	Grn HD HW	Grn LD HW	Grn SYP	Grn HD HW	Grn LD HW	Grn SYP	Grn HD HW	Grn LD HW	Grn SYP
BC-Flute	Small	9.5	1.6	1.6	1.6	4.8	4.8	4.8	4.8	4.8	4.8
		12.7	3.2	1.6	1.6	19.1	6.4	6.4	8	6.4	6.4
		15.9	3.2	3.2	3.2	N/A	N/A	N/A	N/A	N/A	15.9
		19.1	12.7	3.2	6.4	N/A	N/A	N/A	N/A	N/A	N/A
	Medium	9.5	3.2	3.2	1.6	8	6.4	6.4	6.4	6.4	6.4
		12.7	3.2	3.2	3.2	N/A	19.1	19.1	12.7	9.5	8
		15.9	6.4	4.8	4.8	N/A	N/A	N/A	N/A	N/A	N/A
		19.1	N/A	12.7	12.7	N/A	N/A	N/A	N/A	N/A	N/A
	Large	9.5	6.4	9.5	8	N/A	N/A	N/A	N/A	N/A	N/A
		12.7	6.4	6.4	6.4	N/A	N/A	N/A	N/A	N/A	N/A
		15.9	9.5	9.5	9.5	N/A	N/A	N/A	N/A	N/A	N/A
		19.1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Grade 1: less than 12.7 mm (green), Grade 2: 12.7 mm to 25.4 mm (yellow), Grade 3: beyond 25.4 mm increase (red).

Note: Grn HD HW: green high-density hardwood, Grn LD HW: green low-density hardwood, Grn SYP: green southern yellow pine.

Table 2.6 and Table 2.7 present the KD SYP scenarios' amount of top deck board thickness increase required to reduce the corrugated board grade by one level as a function of the different factors for the unit loads built using C-flute and BC -flute boxes, respectively.

To investigate how different factors such as the initial top deck board thickness, pallet wood species, box size, and board grade effect the feasibility of optimizing the strength of the corrugated boxes by changing the stiffness of the pallets, researchers looked at the changes in the proportions of different grade scenarios in response to each variable factor.

Table 2.6. The amount of top deck board thickness required to optimize unit loads consisting of KD SYP pallet and C-flute boxes.

			Amount of top deck thickness increase (mm)		
			0.79 – 0.71 kg/mm ECT	**0.71 – 0.57 kg/mm ECT**	**0.57 – 0.52 kg/mm ECT**
		Initial top deck thickness (mm)	**Kiln-dried Southern Yellow Pine**		
C-Flute	Small	11.1	17.5	N/A	17.5
	Medium		N/A	N/A	N/A
	Large		N/A	N/A	N/A

Note: The deckboard thickness sizes available for kiln-dried southern yellow pine (KD SYP) were limited because the available raw material size only allows the cost-effective production of 11.1 mm and 17.5 mm deckboard thicknesses.

Table 2.7. The amount of top deck board thickness required to optimize unit loads consisting of KD SYP pallet and BC-flute boxes.

			Amount of top deck thickness increase (mm)		
			0.91 – 0.86 kg/mm ECT	**1.09 – 0.91 kg/mm ECT**	**1.27 – 1.09 kg/mm ECT**
		Initial top deck thickness (mm)	**Kiln-dried Southern Yellow Pine**		
BC-Flute	Small	11.1	N/A	N/A	17.5
	Medium		N/A	N/A	17.5
	Large		N/A	N/A	17.5

Note: The deckboard thickness sizes available for kiln-dried southern yellow pine (KD SYP) were limited because the available raw material size only allows the cost-effective production of 11.1 mm and 17.5 mm deckboard thicknesses.

Figure 2.5 shows how the proportions of various grade scenarios changed when different initial top deck thicknesses were used for the pallet design. As the initial top deck

thickness increased, there was a significant reduction in the proportion of grade 1 scenarios. These are the scenarios where it is highly feasible to reduce the corrugated board grade with a reasonable amount of top deck thickness change. The proportion of grade 1 scenarios started from 78% with 9.5 mm initial top deck thickness and decreased to 50%, 24%, and 4% when the initial top deck thickness was 12.7 mm, 15.9 mm, and 19.1 mm, respectively. Correlatingly, the ratio of grade 3 scenarios was almost inversely proportional to the ratio of grade 1 scenarios as the initial top deck thickness increased. The proportion of grade 3 increased from 17% to 31%, 70%, and 91% when the initial top deck thickness was 9.5 mm, 12.7 mm, 15.9 mm, and 19.1 mm, respectively. Unlike other grade scenarios, no consistent trend was found in the proportion of grade 2 scenarios.

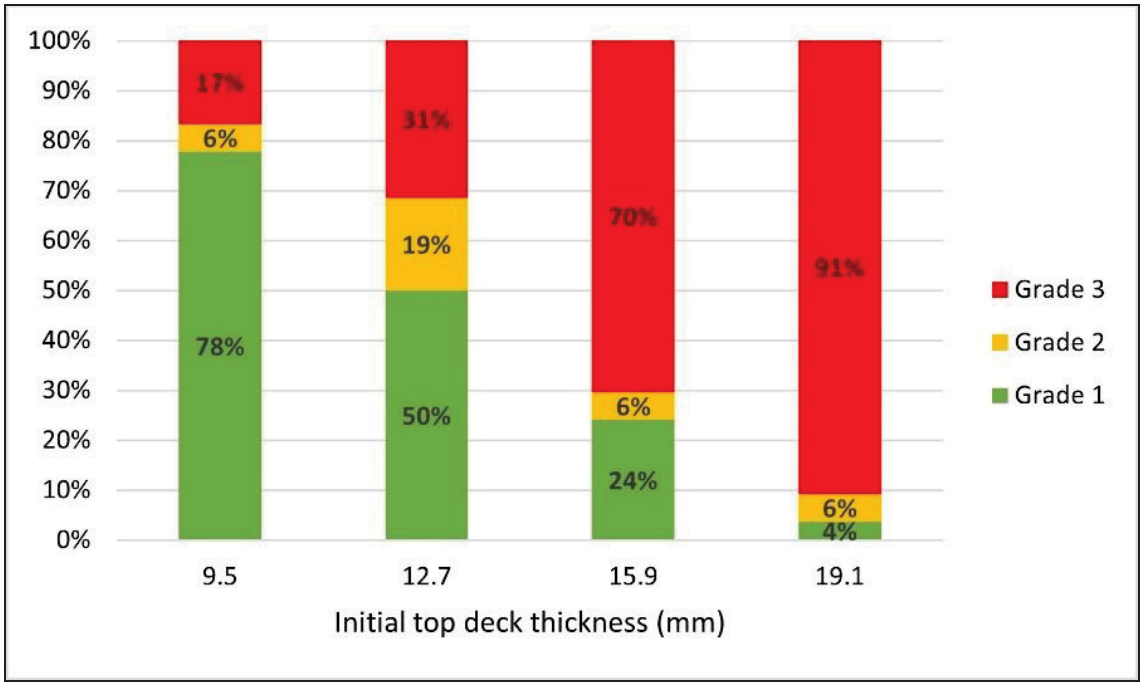

Figure 2.5. Changes in the proportions of the different grade scenarios in response to the initial top deck thickness for green wood scenarios.

Figure 2.6 shows the changes in the proportions of the various unit load scenario grades when different wood species were used to build the pallets. The percent of different grade levels were similar for the scenarios using green low-density hardwood and green SYP with around 40% grade 1, 10% grade 2, and 50% grade 3. KD SYP scenarios behaved

differently than the other wood species scenarios. They had a much lower number of feasible scenarios than the others. Grade 1 scenarios of KD SYP accounted for only 28%, while grade 1 scenarios of green lumber accounted for between 35–40%. The reduction of feasible scenarios might be attributable to the high stiffness of the KD SYP species. A highly stiff top deck will not bend enough to make a difference in board grade when top deck thickness changes. In addition, the results could have been affected by the limited availability of various KD SYP thicknesses. KD SYP lumber required a larger jump in top deck thicknesses than the 1.59 mm increases used with green species.

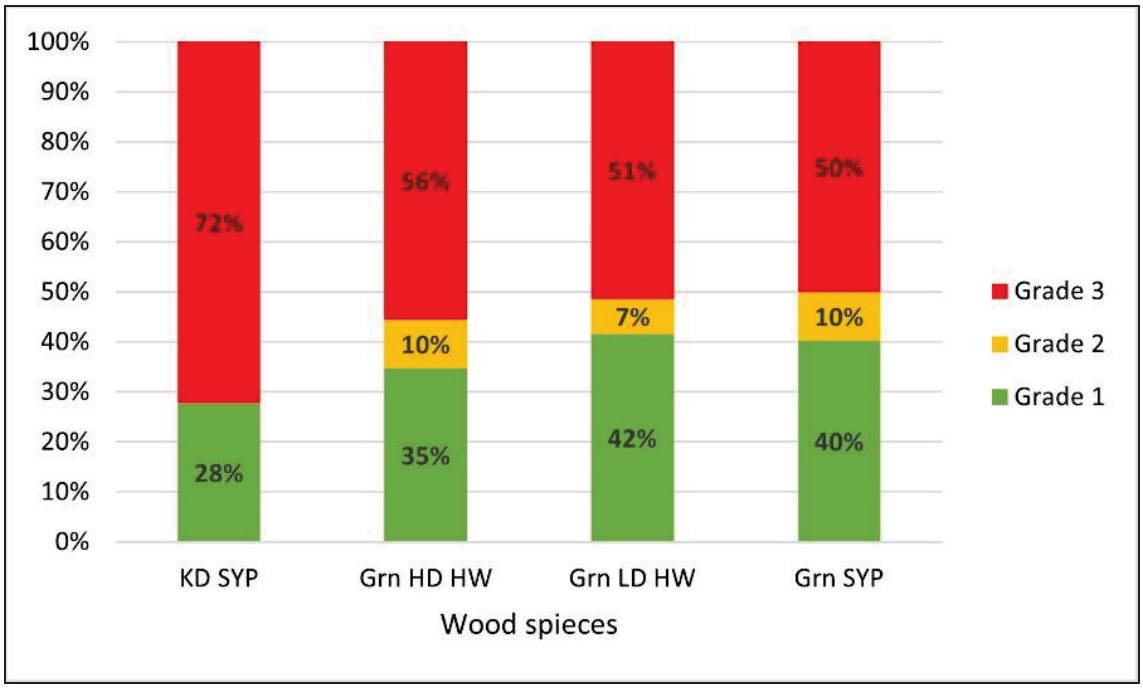

Figure 2.6. Changes in the proportions of the different grade scenarios in response to the pallet wood species.

Note: KD SYP: kiln-dried southern yellow pine, Grn HD HW: green high-density hardwood, Grn LD HW: green low-density hardwood, Grn SYP: green southern yellow pine.

Furthermore, the proportion of the grade 1 scenarios for Grn HD HW was slightly lower (35%) than the other green lumber scenarios (40–42%). Since Grn HD HW does not have a limit on the level of top deck thickness increase, this could provide further evidence that the stiffness of the material affects the feasibility of the design scenario. Overall, the results indicate that the feasibility of using increased deck board thickness to lower the

corrugated boxboard grade decreases when species with higher material stiffness are initially used to construct the pallets.

Similar trends in the proportional changes of different unit load scenario grades were observed from the initial top deck thickness effect and the pallet wood species effect. Both results indicated a significant reduction in the potential to decrease board grade by increasing top deck stiffness when the pallet was initially designed with stiffer pallet wood material. In other words, this unit load optimization method is more effective when the unit load is initially designed using lower stiffness pallets.

Figure 2.7 displays changes in the proportions of different grade scenarios as a function of the range of board grade reduction. It was discovered that for the scenarios where the ECT change is greater between the consecutive board grade levels, the proportion of grade 1 scenarios decreases, and the ratio of grade 3 considerably increases. The ratio of grade 1 scenarios ranged between 41% and 82% for the cases with 0.05 kg/mm to 0.08 kg/mm ECT reduction. On the other hand, the proportion of grade 1 scenarios ranged only between 8% and 28% when it required 0.14 kg/mm to 0.18 kg/mm ECT value reduction. These results also show that the higher the initial board grade is, the more opportunities there are to reduce the board material with minor changes to top deck thickness. For in-stance, the proportion of grade 1 scenarios significantly increased from 41% to 49% and 82% when the board grade reduction range was 0.57–0.52 kg/mm, 0.79–0.71 kg/mm, and 0.91–0.86 kg/mm ECT, respectively. In this analysis, higher board grade also meant that the boxes supported more weight than lower board grade boxes. It indicates that the effect was more prominent for scenarios that had greater unit load weight because having more weight in the boxes causes more bending to the deck boards, which increases stress concentrations on the boxes.

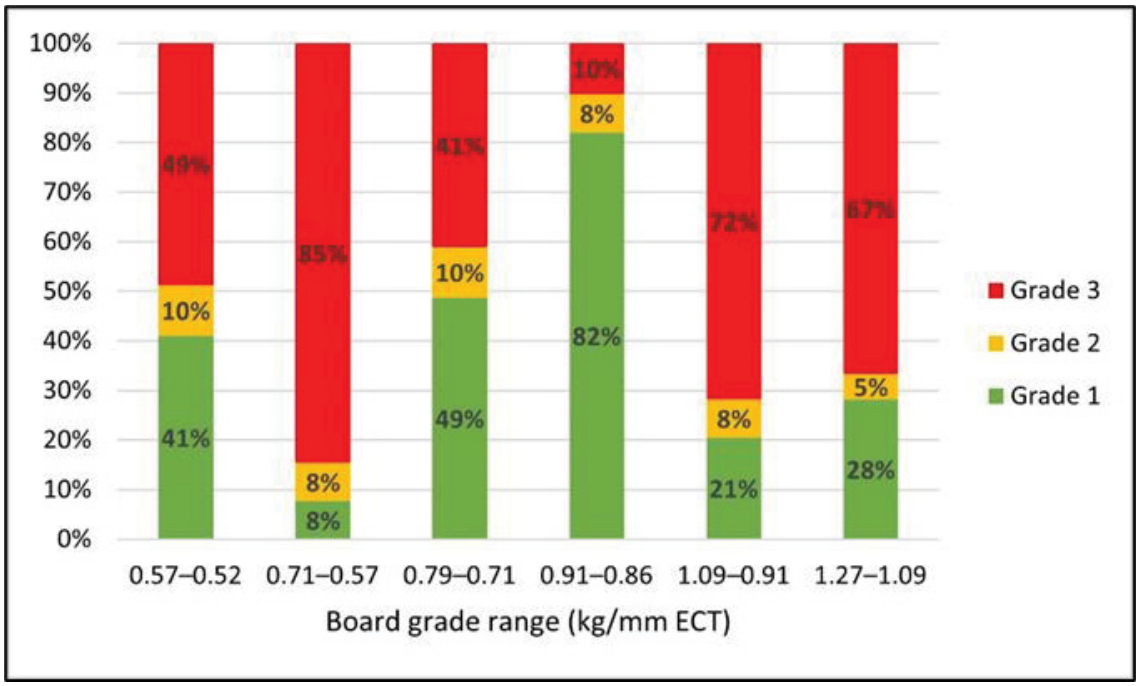

Figure 2.7. Changes in the proportions of the different grade scenarios in response to the range of board grade reduction.

Figure 2.8 shows changes in the proportions of various unit load scenario grades for the three different box sizes. The proportion of the grade 1 scenarios decreased from 57% to 39% and 21% and the proportion of the grade 3 scenario increased from 38% to 47% and 72 % as package size increased from small to medium to large boxes. There was no consistent trend with the proportion of grade 2 scenarios. The results indicated that the feasibility is greater to reduce the corrugated board grade by increasing the thickness of top deck boards for unit loads consisting of small-sized boxes rather than larger ones. Similar to the board grade effect, this trend could be explained by weight differences per unit load. Although each small box held a lighter weight than the medium and large boxes in this analysis, the small box scenarios contained much heavier weight as a whole unit load than the scenarios with larger-sized boxes because these unit loads required more of the small boxes to create the same size load.

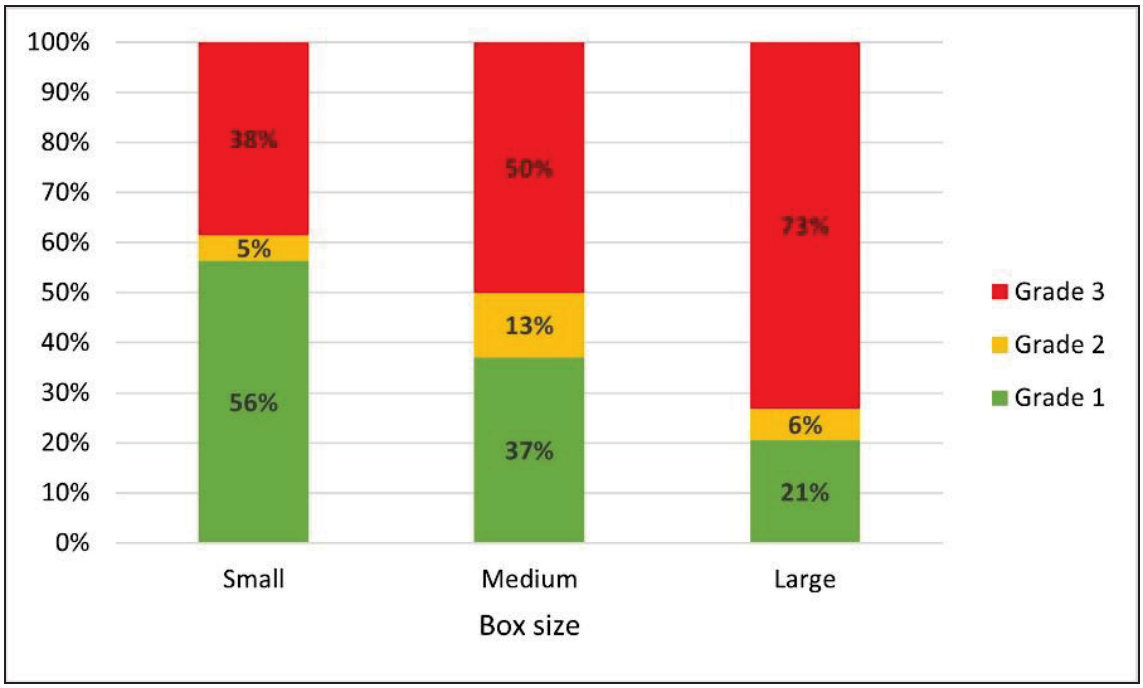

Figure 2.8. Changes in the proportions of the different grade scenarios in response to the box sizes.

Overall, it was found that all investigated variable factors had an observable influence on the feasibility of using an increase in pallet top-deck stiffness to lower the board grade of the corrugated boxes. Unit load scenarios to which it was more feasible to apply the unit load cost optimization method were observed as the initial unit load was de-signed with less stiff pallet top-deck boards; either thinner top deck boards or lower density wood species. For box-related variables, unit loads of smaller-sized boxes, unit loads with a smaller range of board grade reduction, and unit loads with higher initial board grades all created more favorable situations on which to apply the unit load optimization method due to the heavier weight of these unit loads.

2.5 Limitations and Assumptions

1. Only a standard GMA™ style, stringer class, wooden pallet design was investigated in the study.
2. PDS can only run analysis up to 38.1 mm top deck board thickness, so the scenarios requiring top deck boards thicker than 38.1 mm were not simulated. Therefore, the color grading system was applied to show the comparison between these different scenarios.

3. Due to the functional limitations of PDS™ regarding top deck thickness increases, the correlation between pallet stiffness (kg/mm top deck deflection) and the amount of wood material that needed to be added was not investigated.

2.6 Conclusions

The key findings of this study were as follows:

- The benefits of increasing a pallet's top deck thickness to reduce the corrugated board grade diminish as the initial stiffness of the pallet increases.
- There were more opportunities to optimize unit load designs when the ECT values between the different board grade levels were lower.
- There were more possibilities of decreasing board grade when the initial board grade was higher, and/or when the box size was smaller, mostly due to the heavier weight of these unit loads, which caused greater pallet bending. Pallets made of Kiln-Dried Southern Yellow Pine are less likely to be able to be optimized using the investigated methods because of the limited deck board thicknesses that can be cost-effectively manufactured from the available raw materials.

Therefore, this study suggests that companies that use low stiffness pallets or have unit loads of heavy boxes could have more opportunities to optimize their unit loads by increasing the top deck thickness of their pallets.

The study also revealed that changing the top deck board stiffness cannot be done without considering the effects of other factors such as initial top deck board thickness, pallet wood species, box size, and board grade. Therefore, the unit load optimization process that reduces corrugated board grade by increasing top deck stiffness needs to be a holistic process.

The next phase of the project will focus on investigating whether the increase in pallet top-deck stiffness and the resulting reduction in corrugated boxboard grade can create an environmentally beneficial scenario.

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3 Chapter 3: Characterizing Environmental Performance of the Unit Load Optimization Method of Increasing Pallet Top Deck Thickness and Decreasing Corrugated Board Grade

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3.1 Abstract

Trends focusing on packaging sustainability are emerging, not only in consumer packaging, but also in distribution packaging transported in unit load form. Wooden pallets transporting corrugated boxes are the most common unit load type in the United States. Recently, it has been observed that modifying pallet top deck stiffness can significantly affect the strength of corrugated boxes depending on various unit load design factors. It was also discovered that this phenomenon can be used as a tool for packaging cost optimization. However, there is still a knowledge gap regarding how this unit load optimization method could affect the environment. This study was conducted to investigate the environmental effect of optimizing a unit load, achieved by increasing the stiffness of its pallet's top deck and reducing the board grade of the corrugated boxes, using life cycle analysis (LCA). Total of 108 paired unit load designs were investigated, across a range of wood species, pallet top deck thicknesses, corrugated boxes sizes, corrugated flutes, and board grades. Initial and optimized unit load scenarios were designed to ensure that the unit loads offered the same performance. The scope of this study was cradle-to-grave, including raw material production, packaging manufacture, use, and the end-of-life phases of wood pallets and corrugated boxes. The results indicate that optimizing the unit load can offset environmental impacts by up to 23%. Achieved environmental benefits across most of the impact categories were primarily due to the reduction of corrugated material used. Ozone depletion, the exception, was mainly affected by increase in the amount of pallet materials. This study also provided minimum required conditions as preliminary guidance for determining the usefulness of unit load specific analysis, and a sensitivity analysis confirmed these values remain unchanged even with different transportation distances. This study showed that an effective way to reduce the overall environmental footprints of unit loads using the unit load optimization method involves increasing the stiffness of the top decks and reducing the corrugated board grade.

Keywords: Packaging sustainability, distribution packaging, unit load, pallet, corrugated box

3.2 Introduction

Packaging is widely used to contain, protect, preserve, and transport goods. Besides these essential functions, end-of-life (EOL) scenarios for packaging is also a major concern for our current society. With the rise of concern about sustainability issues, the sustainability of packages has also drawn tremendous attention due to the potentially high volume of waste generation. In 2018, about 28% (82 million tons) of municipal solid waste generated in the United States was reported as packaging-related materials (Environmental Protection Agency, 2020). As the importance of sustainability has increased, packaging has rapidly become recognized as an area that requires immediate attention by consumers, industry, and policymakers in order to help solve the problems that the world is facing. For instance, a global coalition of companies in the fashion and textile industries announced their shared environmental goal of eliminating plastic materials from their consumer packaging in response to sustainable packaging demands from their customers (The Fashion Pact, 2020). Furthermore, U.S. governmental organization, the Environmental Protection Agency (EPA), created the Sustainable Materials Management (SMM) program, which promotes the use of recyclable and processable packaging materials (U.S. Environmental Protection Agency, 2017).

Distribution packaging plays a crucial role in the transportation of goods, ensuring the primary packaging, safety, efficiency, and cost-effectiveness in getting goods to wherever consumers can easily access them. Eighty percent (80%) of distribution packaging in the United States is in unit load form which consists of packaging, pallets, and the material handling system (Raballand & Aldaz-Carroll, 2007; White & Hamner, 2005). Pallets are ubiquitous in the supply chain with 2.6 billion pallets circulating in the United States annually (Freedonia Group, 2015). Out of all pallet materials, wood dominates the industry with 94% of the market share (Modern Materials Handling, 2021). Approximately 804 million wooden pallets were newly produced or recycled in 2016 from various industries in the United States (Gerber et al., 2020). In addition, the predominant type of packaging is the corrugated box, which accounts for 72% of the packaging materials used to build unit loads (McCrea, 2020).

As the unit load accounts for a large share of the distribution packaging system, it is crucial to understand and evaluate the environmental impact of the unit load. Several

studies have compared the environmental impact of wooden pallets to the impact of pallets made from different materials, manufacturing systems, or alternative distribution packaging systems using LCA (Anil et al., 2020; Bengtsson & Logie, 2015; Kočí, 2019; Lee & Xu, 2004). Other studies investigated environmental hotspots and developed a life cycle inventory for wooden pallets to help decide on designing or choosing an environmentally friendlier pallet (Alanya-Rosenbaum et al., 2021; Carrano et al., 2014; García-Durañona et al., 2016; Park et al., 2018). Many previous researchers from various fields have assessed the environmental impact of corrugated boxes when they are used as part of a whole packaging system and as compared with reusable alternative packaging systems (Berlin, 2002; Dimyati & Singgih, 2019; Hospido et al., 2003; Koskela et al., 2014; Levi et al., 2011; Munasinghe et al., 2017; Silvenius et al., 2014; Thorbecke et al., 2019).

Meanwhile, the environmental impacts of unit load components have been studied focusing on the impact of pallets and corrugated boxes separately. Up until now, there have been no attempts to holistically optimize the environmental impact of the unit load using the interactions between these two components. Understanding the interactions between unit load components is essential to optimizing them to be safer, more cost-effective, and environmentally friendly. In recent years, the effect of the stiffness level of the wooden pallet top deck boards on the performance of corrugated boxes was broadly studied by researchers (Baker, 2016; Kim et al., 2021; Phanthanousy, 2017; Quesenberry et al., 2020). Quesenberry et al. (2020) found that the stiffness of wooden pallets' top deck boards affects the strength of corrugated boxes up to 37% when corrugated boxes are asymmetrically supported. He also found that this phenomenon can be used as a cost optimization method for unit loads by increasing the stiffness of the wooden pallet top deck boards and decreasing the board grade of corrugated boxes (Quesenberry et al., 2020). Kim et al. (2021) further investigated this unit load cost optimization method, and they found that it can be affected by various unit load design factors like pallet wood species, top deck thickness of initial unit load scenario, corrugated box size, and board grade. Both studies expressed that this optimization method could, not only be used for cost optimization, but could also possibly be a method of improving the environmental performance of current unit load designs at the same time.

Therefore, this unique study investigates the environmental effects of the unit load optimization method previously proposed by Quesenberry et al. (2020) which allows for the decrease of the board grade of corrugated boxes by increasing the thickness of the pallets' top deck boards. This work (1) contributes new knowledge regarding how unit loads can be holistically, and environmentally-optimized based on the interactions between components, (2) demonstrates hotspots of environmental impact when optimizing unit load designs, and (3) provides thresholds to be followed to figure the environmental advantages of this unit load optimization method.

3.3 Materials and Methods

This study mainly employed the life cycle analysis (LCA) method to compare the environmental impact of both the initial and the optimized unit load designs, which comply with international standard LCA guidelines ISO 14040:2006 and ISO 14044:2006 (ISO, 2006a, 2006b).

3.3.1 Goal and Scope Definition

The main aim of this study was to investigate the environmental effects of optimizing a unit load by increasing the stiffness of the pallets' top deck boards and reducing the board grade of its corrugated boxes using LCAs. The LCAs compared the environmental performance of multiple initial and optimized unit load scenarios with a cradle to grave perspective. This study included raw material production, packaging manufacturing, distribution, and end-of-life options (EOL). However, this study excluded the life cycle of packaged items from the system boundary due to their high variability. Figure 3.1 presents a drawing of the system boundaries considered in this study. Also, the geographical scope was limited to the southeastern United States due to the variability of local wood species supplied for wood pallet manufacturing.

The optimization method employed in this study required different amounts of pallet top deck material increase. It also resulted in different amounts of corrugated box material decrease depending on various unit load design factors (Kim et al., 2021). Hence, this study compared a wide range of paired initial and optimized unit load scenarios to investigate at what point they cross the line to show measurable environmental benefits

through this unit load optimization method. Therefore, this study was not able to select specific load capacities for the functional unit. The functional unit for this study was defined as double-stacked unit loads with the same maximum safe load capacity under floor stacking conditions. These unit loads needed to be comprised of a 1219.2 mm x 1016 mm Grocery Manufacturers Association (GMA) style, stringer-class, wooden pallet with identical corrugated boxes manufactured from the same flute-size corrugated board.

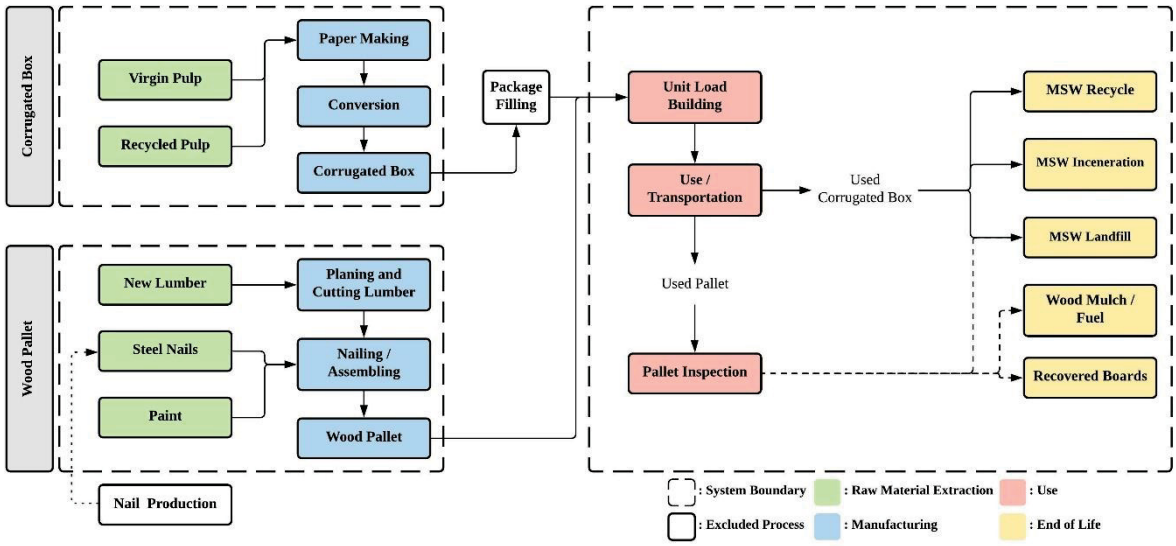

Figure 3.1. The schematization of the unit load system boundary.

3.3.2 Unit Load Scenario Employment

In this study, the environmental performance of multiple pairs of initial and optimized unit load scenarios, composed of wooden pallets and corrugated boxes, were compared to each other. A total of 108 pairs of unit load scenarios were employed from the authors' previous study Kim et al. (2021). Kim et al. (2021) designed an extensive list of unit load scenarios with varying factors such as initial top deck board thickness, pallet wood species, box size, and board grade covering a wide range of common unit load designs. The unit load scenarios were classified into three grades according to the amount that the top deck board thickness increased. Among these unit load scenarios, only scenarios with which it was found to be feasible to apply the unit load optimization method from the manufacturing standpoint, grade 1 (less than 12.7 mm top deck thickness increase) and grade 2 (12.7 mm to 25.4 mm top deck thickness increase), were used for this study. The optimized unit load scenarios listed in that research paper were created from the initial

unit load scenarios by increasing the stiffness (thickness) of the pallet top deck boards and reducing the board grade of corrugated boxes while maintaining identical box performance. Detailed specifications of the investigated unit load scenarios composed of green high-density hardwood (HD HW) pallets, green low-density hardwood (LD HW) pallets, green southern yellow pine (GSYP) pallets, and kiln-dried southern yellow pine (KD SYP) pallets were described in Table A1, A2, A3, and A4, respectively.

3.3.3 Ranked Scenario Analysis

In order to effectively evaluate a wide range of unit load scenarios, four different pallet wood species groups were analyzed separately and ranked using a unit load optimization ratio (UOR) developed by the authors.

UOR is a ratio of the decreased weight of corrugated materials to the increased weight of pallet materials; both of which change during this unit load design optimization process. Within this method, it is assumed that the weight of the corrugated board must decrease, and the weight of the pallet materials must increase. The UOR was calculated by following equation 3.1:

$$UOR = \frac{C_i - C_o}{P_o - P_i}$$

Equation 3.1 UOR calculation.

where:

UOR = Unit load optimization ratio

C_i = Weights of corrugated boxes from initial unit load design

C_o = Weights of corrugated boxes from optimized unit load design

P_i = Weights of wooden pallets from initial unit load design

P_o = Weights of wooden pallets from optimized unit load design

Higher ratios reflect a smaller amount of weight increase of pallet materials to decrease in the weight of corrugated materials, which also can be assumed to be closer to a best-case scenario. The worst-case solutions have a lower ratio, which means there was a greater increase in the weight of pallet materials required to decrease the weight of corrugated

materials. Unit load scenarios were ranked and listed in the order of material utilization according to the UOR of each scenario.

The weight of wooden pallets and corrugated boxes from each pair of initial and optimized unit load scenarios were determined to calculate UOR. The weights of wooden pallets and corrugated boxes were computed by the industry-accepted pallet design software Pallet Design System™ (PDS™) v. 6.2 (National Wooden Pallet & Container Association, Alexandria, VA, USA) and the unit load design software Best Load™ v.4.0 (White & Company LLC, Blacksburg, VA, USA), respectively. Both softwares use finite element models to predict the performance of pallets and the packages shipped on pallets. Specifications of wooden pallets and corrugated boxes obtained from the previous study were entered into the corresponding software.

Once the unit load scenarios were ranked by UOR, six pairs of initial and optimized unit load scenarios from HD HW group, LD HW group, and GSYP group were selected for LCA based on regular interval ranking (e.g., 1st position, 3rd position, 5th position). Exceptionally, all available unit load scenarios (only five pairs) were selected from the KD SYP group due to the limited number of optimizable scenarios. Among these scenarios, the unit load scenario with the lowest UOR from each wood species group was defined as the worst case scenario. And, the unit load scenario with the highest UOR was defined as the best case scenario in terms of proportional material utilization.

3.3.4 Environmental Performance Difference Analysis

The difference in environmental performance of the initial unit load designs and the optimized unit load designs from each of the scenarios selected at regular intervals for each wood species group were studied to investigate whether the unit load optimization method had environmental benefits or not. Positive environmental impact difference (+%) indicates that optimizing these unit load designs lower environmental burdens, and on the contrary, negative environmental impact difference (-%) reflects the fact that optimizing these unit loads generate environmental burdens instead.

3.3.4.1 Life Cycle Inventory Analysis

Life cycles of unit load scenarios were modeled through commonly used LCA software SimaPro 9.0 (PRe Consultants, Amersfoort, The Netherlands). The secondary inventory data regarding pallet weights were obtained from PDS™ v. 6.2. Unit load design software Best Load™ v.4.0 was utilized to obtain the secondary inventory data of corrugated box weights. The U.S. LCI database, which traditionally represents U.S. regions, was mainly utilized for LCA modeling in SimaPro 9.0. The Ecoinvent v.3 database was also employed for LCA modeling to fill the existing inventory gaps within the U.S. LCI database.

Unit Load Raw Material Production

Inventory data regarding wooden pallet, raw-material production was modified from the most up-to-date life cycle inventory of wooden pallets in the United States which was developed by Alanya-Rosenbaum et al. (2021). Values were adjusted according to the density of the four different wood species used in pallet manufacturing: green high-density hardwoods, green low-density hardwoods, green southern yellow pine, and kiln-dried southern yellow pine. The density of each wood species was calculated from PDS™ by dividing the weight (kg) of the pallets made from different wood species by each pallets' volume (m3). Inventory data was also broken down to the level of 'per 1 kg of wooden pallet raw material production' in order to be able to universally apply this data to the various unit load scenarios. Modified pallet raw materials production phase inventory data is listed under Appendix B in Table B1-B4.

The inventory data for corrugated box raw material production was adopted from the comprehensive LCA study done on the average corrugated products in the U.S. by the National Council for Air and Stream Improvement (2017) due to its similar geographical scope as this study.

Unit Load Manufacture

For modeling the pallet assembly and corrugated box manufacturing, inventory data developed from the previous studies were also employed without modification since the input and output of data for unit load component manufacturing does not dramatically change due to unit load design factors. The average input and output data for the pallet

manufacturing process was collected from Alanya-Rosenbaum et al. (2021) due to their similar geographical scope as this study and the recentness of information. Inventory data for the corrugated box production process was obtained from the National Council for Air and Stream Improvement (2017).

Transportation

Assumed transportation modes and travel distances for wooden pallets and corrugated boxes are presented in Table 3.1. Road transportation was mainly considered for wooden pallets due to this study's geographical scope, which also showed that wooden pallets are supplied and consumed locally. Only single use pallet scenarios were considered. Both road and rail distribution were considered for corrugated boxes since they could be supplied from anywhere in the United States. However, road transportation was regarded as the primary mode of distribution for corrugated boxes in order to follow the geographical scope of this study.

Table 3.1. Transportation data: distribution modes and distances considered for unit load components.

Product	Item	Truck		Rail	
		Weighting (%)	Distance (km)	Weighting (%)	Distance (km)
Wooden pallet	Raw material to manufacturer	100	148	-	-
	Pallet manufacturer to product manufacturer	100	148	-	-
	Unit load transportation (use)	100	1207	-	-
	EOL transportation	100	148	-	-
Corrugated box	Wood logs to pulp and paper mils	98.4	159	1.6	1577
	Wood chips to pulp and paper mils	94.5	299	5.5	1674
	Recovered fiber to pulp and paper mils	85.4	241	14.6	505
	Pulp to pulp and paper mils	80.1	262	19.8	1511
	Chemicals	72	217	28	1333
	Containerboard to converting facility	80.1	262	19.9	1511
	Corrugated sheets to product manufacturer	80.1	262	19.9	1511
	Product to use	95.7	283	4.3	2446
	Unit load transportation (use)	100	1207	-	-
	EOL transportation	87.4	241	12.6	505

End of Life of Unit Load

Unit load components' EOL phases were modeled based on the U.S. national data and details from the literature. At the end of a wooden pallet's life cycle, unbroken boards were recovered for reuse or repair of the other pallets, and the rest were landfilled, used for boiler fuel, or used for mulch and animal bedding (Alanya-Rosenbaum et al., 2021). Corrugated boxes end up being recycled in many cases, combusted for energy, or landfilled in fewer cases (U.S. Environmental Protection Agency, 2020). Table 3.2 presents the distribution of the EOL scenarios for each unit load component.

Table 3.2. End of life stage of unit load.

	Wooden pallets	Corrugated boxes
Recovered boards	37.3 %	N/A
Fuel	17.3 %	N/A
Mulch and animal bedding	40.4 %	N/A
Landfill	5 %	15.4 %
Combustion	N/A	3.7 %
Recycle	N/A	80.9 %

3.3.4.2 Life Cycle Impact Analysis

A midpoint-oriented life cycle impact analysis method, Tool for the Reduction and Assessment of Chemical and other Environmental Impacts 2.1 (TRACI 2.1), was utilized to calculate the environmental impact generated by the inputs and outputs of the unit load life cycle. This evaluation method was selected for calculations due to its matching geographical scope with this study. TRACI 2.1 was developed to reflect the environmental situation of U.S locations by U.S. Environmental Protection Agency (EPA). A total of ten impact categories were calculated and presented including ozone depletion (kg CFC-11 eq), global warming (kg CO_2 eq), smog (kg O_3 eq), acidification (kg SO_2 eq), eutrophication (kg N eq), carcinogenics (CTUh), non carcinogenics (CTUh), respiratory effects (kg PM2.5 eq), ecotoxicity (CTUe), and fossil fuel depletion (MJ surplus).

3.3.5 Minimum Required Condition Analysis

The previous environmental differences analysis reported the crossing points between the negative and positive environmental impacts of the unit load optimization method. However, that analysis did not have a granular enough number of investigated scenarios to be able to find the exact first point where the positive environmental impact could be observed. Accordingly, a minimum required condition analysis was conducted, where the finer steps around the crossing points from the previous analysis were investigated. The

first unit load scenarios for each wood species group that showed an environmental benefit within all impact categories from the regular interval analysis were set as the base scenarios. The environmental performance difference analysis was repeated from the base scenarios to the scenarios that fell below 0% of the environmental performance difference (the break-even line) for any of the impact categories in descending order of the unit loads' rank for the minimum required condition analysis. The minimum required conditions to improve the environmental performance by optimizing unit load design were defined as UORs that will cause the unit loads to cross the environmental performance break-even line in all investigated impact categories for the first time.

3.3.6 Sensitivity Analysis

Sensitivity analysis on different ranges of use transportation, where wide variation occurs, was also conducted. Ranges of use transportation distance is a parameter that significantly varies depending on various reasons such as manufacturer's business coverage, location, product sensitivity, and more. Unit load scenarios with minimum required conditions for each wood species group were selected as base cases for sensitivity analysis. Two shorter and two longer ranges from the base cases of the range of use transportation distances were investigated. Two shorter distances were 100 km and 500 km, while two longer distances were 1,500 km and 2,000 km, and the base case was set at a 1,207 km range of use transport distance.

3.4 Results and Discussion

3.4.1 Ranked Scenario Analysis Results

Figure 3.2 plotted the adopted unit load scenarios in ascending order of ranking based on the unit load optimization ratio (UOR) calculated for each wood species group. Columns colored red in Figure 3.2 indicate the unit load scenarios chosen at regular intervals to be utilized for the life cycle analysis. The best case scenarios were found to be unit load scenarios with UOR of 3.200, 3.733, 4.480, and 1.918 for HD HW, LD HW, GSYP, and KD SYP, respectively. The worst case scenarios from HD HW, LD HW, GSYP, and KD SYP had UOR of 0.035, 0.021, 0.023, and 0.16, respectively.

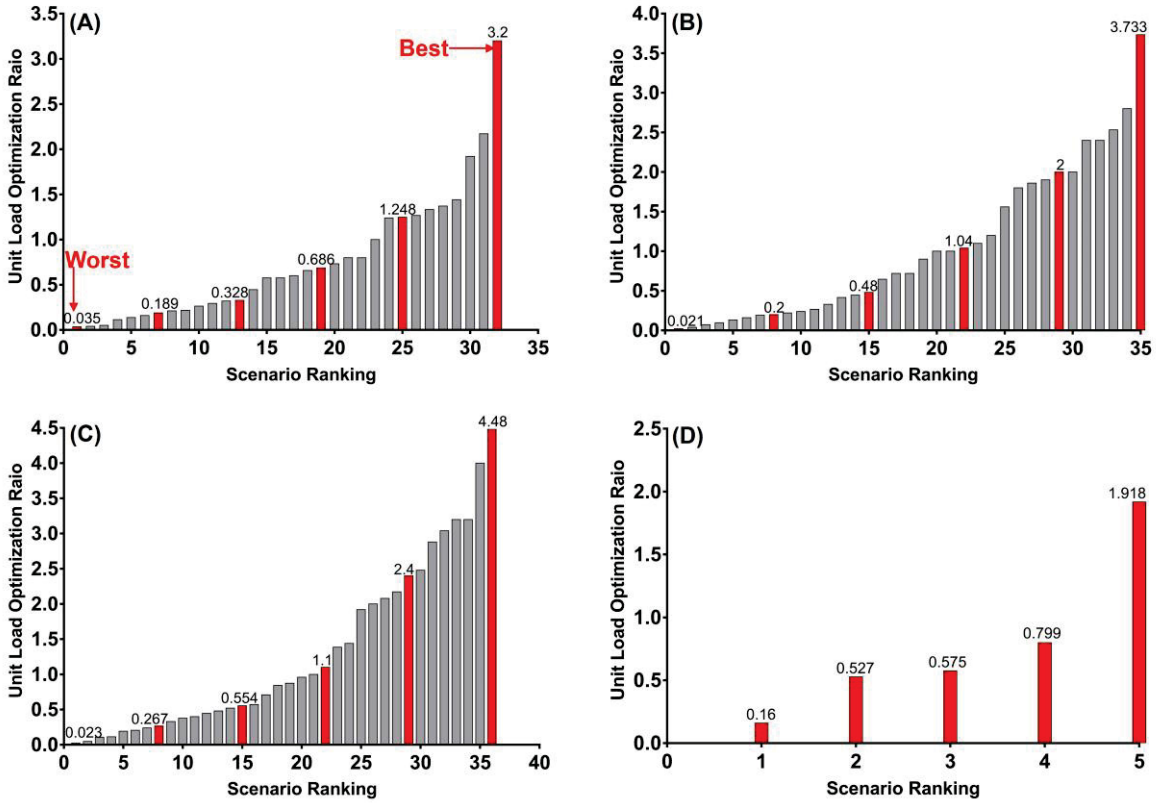

Figure 3.2. Rankings of investigated unit load scenarios from various wood species groups based on unit load optimization ratio. (A) displays results of HD HW group, (B) displays results of LD HW group, (C) displays results of GSYP group, and (D) displays results of KD SYP group.

* Note: Red columns within plots indicate unit load scenarios selected for environmental analysis.

3.4.2 Environmental Performance Difference Analysis Results

Researchers compared and plotted the differences in environmental impacts between the initial unit load designs and the optimized unit load designs from each wood species group in order to investigate whether the unit load optimization method generated environmental benefit or environmental burden.

Figure 3.3 reports the environmental impact differences between initial unit load designs and optimized unit load designs within the HD HW group. It was observed that the unit load optimization method does not always create environmental benefits in the HD HW group. Optimized unit load design scenarios with a UOR of 0.035 generated up to

22.57% more negative environmental impacts than the initial unit load design in all impact categories except acidification. Although the unit load optimization method was not environmentally beneficial for the low UOR scenario, it started generating environmental benefits as the UOR increased. More than half of the impact categories (seven impact categories - excluding ozone depletion, eutrophication, and ecotoxicity) for the unit load scenario with UOR of 0.189 showed environmental benefits by optimizing unit load design. Furthermore, it was discovered that optimizing unit load scenarios with UOR of 1.248 or higher improved environmental performance up to 22.93% in all investigated impact categories. Additionally, the unit load scenario with 1.248 UOR was employed as the base scenario in the minimum required condition analysis. This was the first scenario that crossed the environmental performance difference break-even line during regular interval analysis.

Figure 3.4 presents the environmental impact difference of the LD HW group's initial unit load designs and optimized unit load designs. Like the HD HW group, optimizing the first investigated unit load scenario with a UOR of 0.021 decreased environmental performance up to 35% in most impact categories except acidification. As the UOR increased, more and more impact categories started to show environmental benefits from the unit load optimization method. The unit load scenario with a UOR of 0.2 reported improvements in environmental performance from six impact categories, excluding ozone depletion, eutrophication, carcinogenics, and ecotoxicity. Moreover, all impact categories indicated that optimizing the unit load could generate environmental benefits as much as 22.85% within LD HW group. The base scenario for minimum required condition analysis was set to 2 UOR in this case.

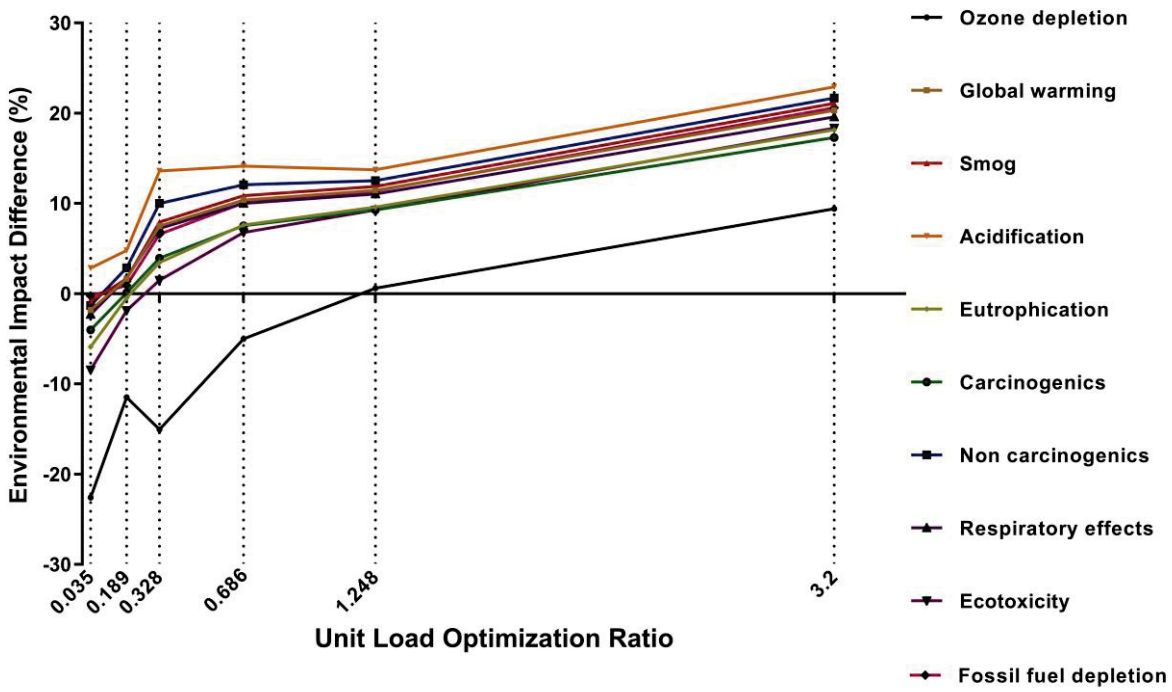

Figure 3.3. The environmental impact difference of initial and optimized unit load designs within the HD HW group.

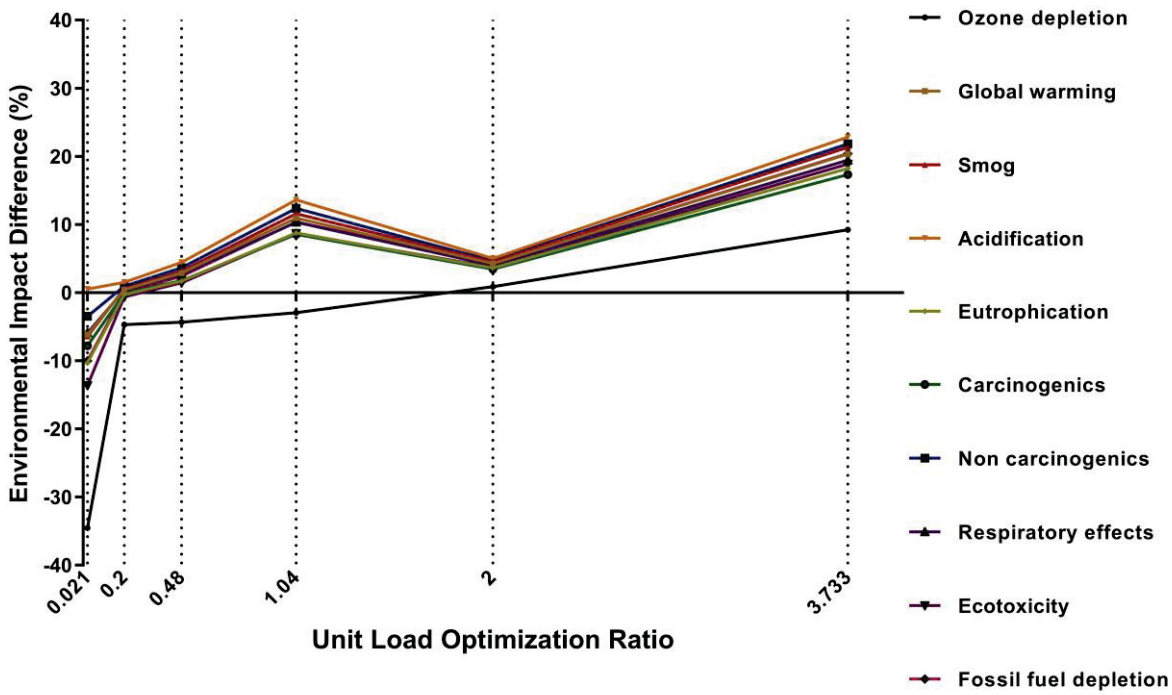

Figure 3.4. The environmental impact difference of initial and optimized unit load designs within the LD HW group.

Figure 3.5 displays the difference in the environmental performance of initial unit load designs versus the optimized unit load designs from the GSYP group. The trend of optimizing unit load scenarios with lower UORs causing diminishing environmental performance was also observed in the GSYP group. Optimizing the worst case scenario (0.023 UOR) decreased the overall environmental performance by as much as 35.23%, and an environmental benefit was only observed for acidification. GSYP group results also followed the trend discovered in the HD HW and LD HW groups where the number of impact categories showing environmental benefits from unit load optimization escalates as UOR increases. Consequently, the best case scenario in the GSYP group (4.48 UOR) showed as much as 20.48% increase in environmental benefits in all impact categories when applying the unit load optimization method. There were environmental benefits in all impact categories when the unit load was designed with a UOR of 2.4 or higher in the GSYP group.

Figure 3.6 shows the environmental impact difference of the initial and optimized unit load designs belonging to the KD SYP group. As the UOR escalates, improvement in the environmental performance through the optimization of the unit loads was also observed in many impact categories in the KD SYP group. The best case scenario improved the environmental impact of unit load up to 13.16%. However, the KD SYP group reported a slightly different trend from the other wood species groups. Previous results from the HD HW group, LD HW group, and GSYP group showed that optimizing the unit load can improve the environmental performance of unit load in all impact categories when the UOR is higher than specific points. In contrast, the KD SYP group could not enhance the environmental performance of unit load in terms of ozone depletion even with the maximum possible UOR. In other words, KD SYP unit load scenarios cannot expect full environmental benefits from this unit load optimization method.

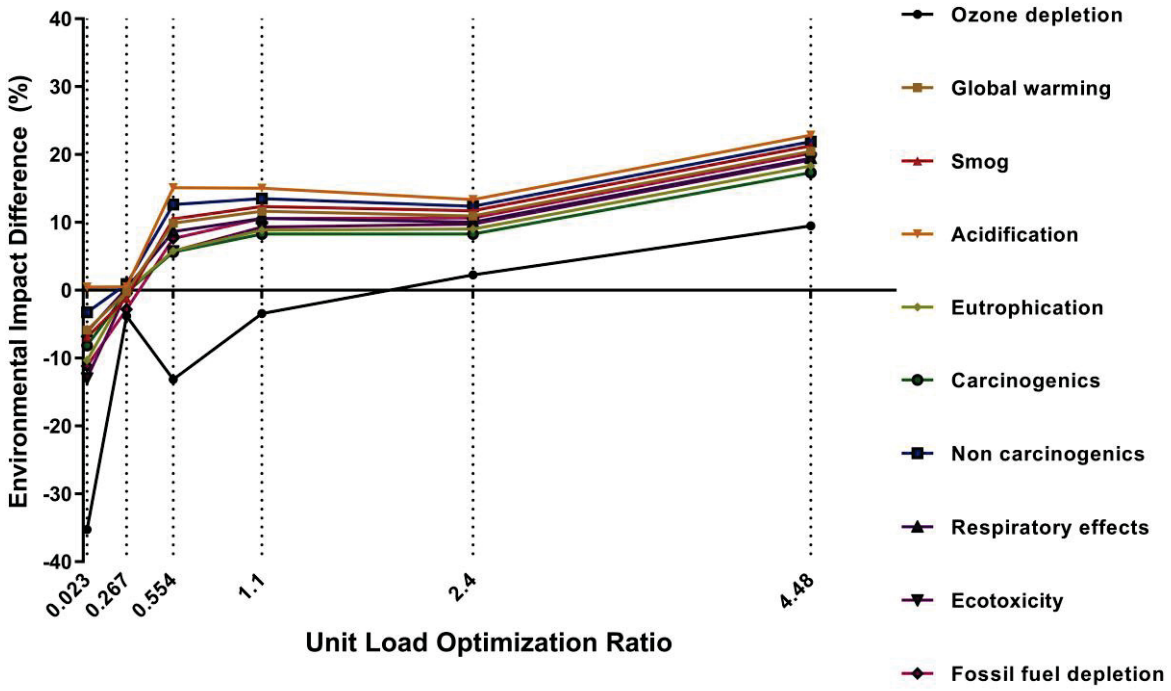

Figure 3.5. The environmental impact difference of initial and optimized unit load designs within the GSYP group.

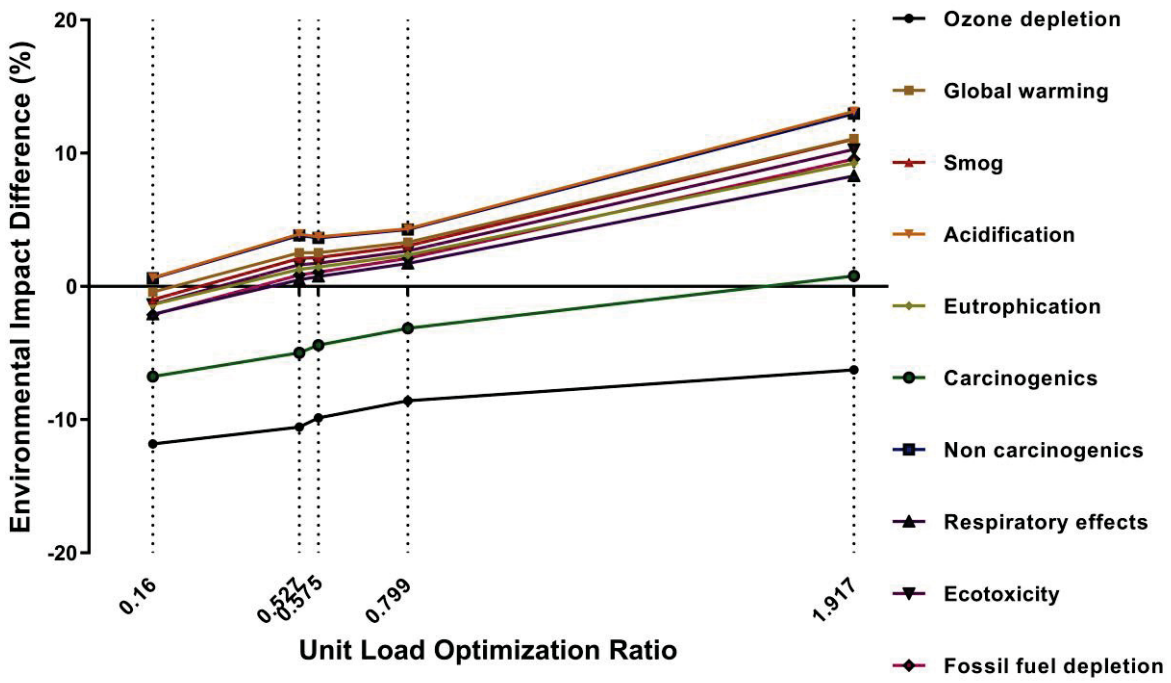

Figure 3.6. The environmental impact difference of initial and optimized unit load designs within the KD SYP group.

Overall, it was found that the investigated unit load optimization method could improve the environmental performance of unit loads when the unit load scenario has a specific UOR or higher. The first UORs for unit load scenarios that started showing environmental benefits in terms of all impact categories from the regular interval analysis were 1.248, 2, and 2.4 for HD HW, LD HW, and GSYP groups, respectively. On the contrary, the KD SYP group showed only a low environmental performance increase in most impact categories after optimizing its unit load design. In addition, KD SYP group could not achieve environmental benefits, in terms of ozone depletion, from any of the optimization scenarios. This exception was predominantly influenced by the limited number of KD SYP deck board sizes that can be effectively manufactured from the raw material. Therefore, KD SYP scenarios investigated in this study required a significant increase in wood materials (only possible to increase from 11.1 mm to 17.5 mm) and there were not enough consecutive decreases in corrugated boards to offset the environmental burden of the unit load, even though the corrugated material requires more processing and wood requires less processing.

Although the KD SYP group results did not show environmental performance improvement in ozone depletion, the general trend of environmental benefits observed from more impact categories as the UOR increased remains unchanged within all investigated wood species groups. An increasing the UOR means that the unit load optimization process is requiring less of an increase in pallet wood materials proportional to the decrease in corrugated materials. In other words, a higher UOR utilizes less of a decrease in the chemically unprocessed wood materials compared to the chemically processed wood material increase during the unit load optimization process. This leads to impact categories that are heavily affected by the corrugated box related phases which advances their environmental impact performance earlier than the impact categories that are less affected by the corrugated box related phases. Further discussion on this matter can be found in the contribution analysis section below.

However, it was also discovered that unit load scenarios with a higher UOR do not necessarily mean they'll show higher environmental performance improvement. Up and down in the level of environmental impact differences were consistently observed

regardless of the amount of UOR increase. This could be due to the fact that UORs were only based on the proportion of material utilization, and do not account for the absolute amount of pallet and corrugated material change. In other words, unit load scenarios with lower UORs may have higher amounts of pallet and corrugated material changes during optimization than unit load scenarios starting with higher UORs. Since the UOR is only based on material efficiency, unit load scenarios with higher than or equal UORs to unit load scenarios that have crossed the break-even line for the first time can always expect environmental benefits by applying the unit load optimization method, but to different degrees. Therefore, the UOR that first crosses the environmental performance break-even line suggests the minimum required conditions to improve the environmental performance of the initial unit load design. These specific minimum required conditions for each wood species group were further investigated in the next section. It also means unit load designers need to run their own environmental performance difference analysis in order to figure the exact degree of environmental benefit received by applying the unit load optimization method to their specific unit load designs.

Figure 3.7 presents contribution analyses on six environmental impact categories: global warming potential, smog creation, fossil fuel depletion, eutrophication, acidification, and ozone depletion for each wood species groups' best case scenarios. The most significant contributors to global warming potential and acidification were the corrugated box raw materials production phases. Two leading contributors to smog creation and fossil fuel depletion were corrugated box raw materials production and transportation phases. Eutrophication was predominantly affected by corrugated raw materials production and box manufacturing processes. Ozone depletion was heavily affected by the pallet raw materials production phase, followed by the corrugated box raw materials production phase.

Regarding the trend of ozone depletion, this trend was exceptionally difficult to generate a positive impact through the unit load optimization method; especially when compared to all other impact categories. It required a relatively high UOR before observing any environmental benefit in terms of ozone depletion, and unit load scenarios in the KD SYP group were not able to create environmental benefit even with the high UOR. This is mainly because ozone depletion is governed by pallet raw material associated factors,

mainly heating for kiln dry process of lumber, while corrugated box related processes controlled the other impact categories. This study's adopted unit load optimization method basically adds chemically unprocessed wood materials to the pallets top deck in order to decrease the chemically processed materials in the corrugated boxes. Consequently, environmental benefits in terms of ozone depletion, which is mainly governed by the pallet raw materials production phase, cannot easily be achieved until there is sufficient reduction of corrugated box raw materials phase to mitigate the effects of the pallet raw materials production phase.

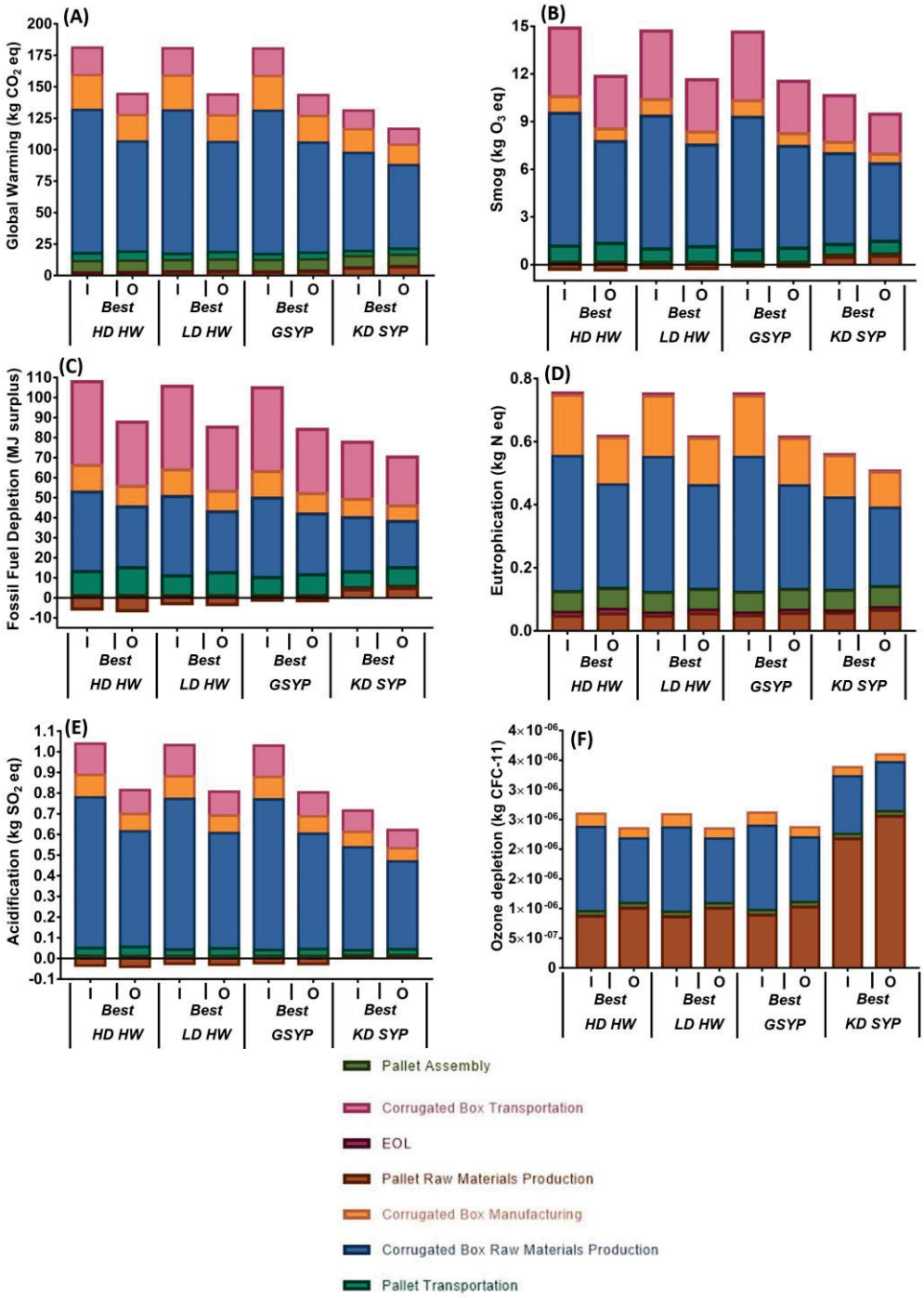

Figure 3.7. Contribution analyses for the best case scenarios from the HD HW, LD HW, GSYP, and KD SYP groups. (A) shows global warming potential, (B) shows smog creation, (C) shows fossil fuel depletion, (D) shows eutrophication, (E) shows acidification, and (F) shows ozone depletion. I indicates initial case and O indicates optimized case.

3.4.3 Minimum Required Condition Analysis Results

This section estimates the minimum required conditions for each wood species group to estimate the environmental advantages obtained through the optimization of the unit load designs. Figure 3.8 presents changes in the environmental performance of unit load scenarios: from the first unit load scenario that falls below the environmental performance break-even line to the first unit load scenario above that line during regular interval analysis for each wood species group. The results revealed that the UOR of 1.24, 1.56, and 1.92 are the minimum required conditions for HD HW group, LD HW group, and GSYP group, respectively, to obtain environmental benefits in all impact categories by optimizing unit load. However, unit load designers need to look at these values as a preliminary decision-making tool not as the exact values to use in deciding whether they should conduct an LCA on a specific unit load scenario. Many other minor factors can change their unit load's specific minimum required condition depending on the supply chain environment.

As mentioned in the previous section, there are challenges to using UOR to directly predict the exact environmental impact of optimizing specific unit load scenario. However, UOR still adds the value of easing the process of predicting the potential of environmental advantages of optimizing specific unit load design.

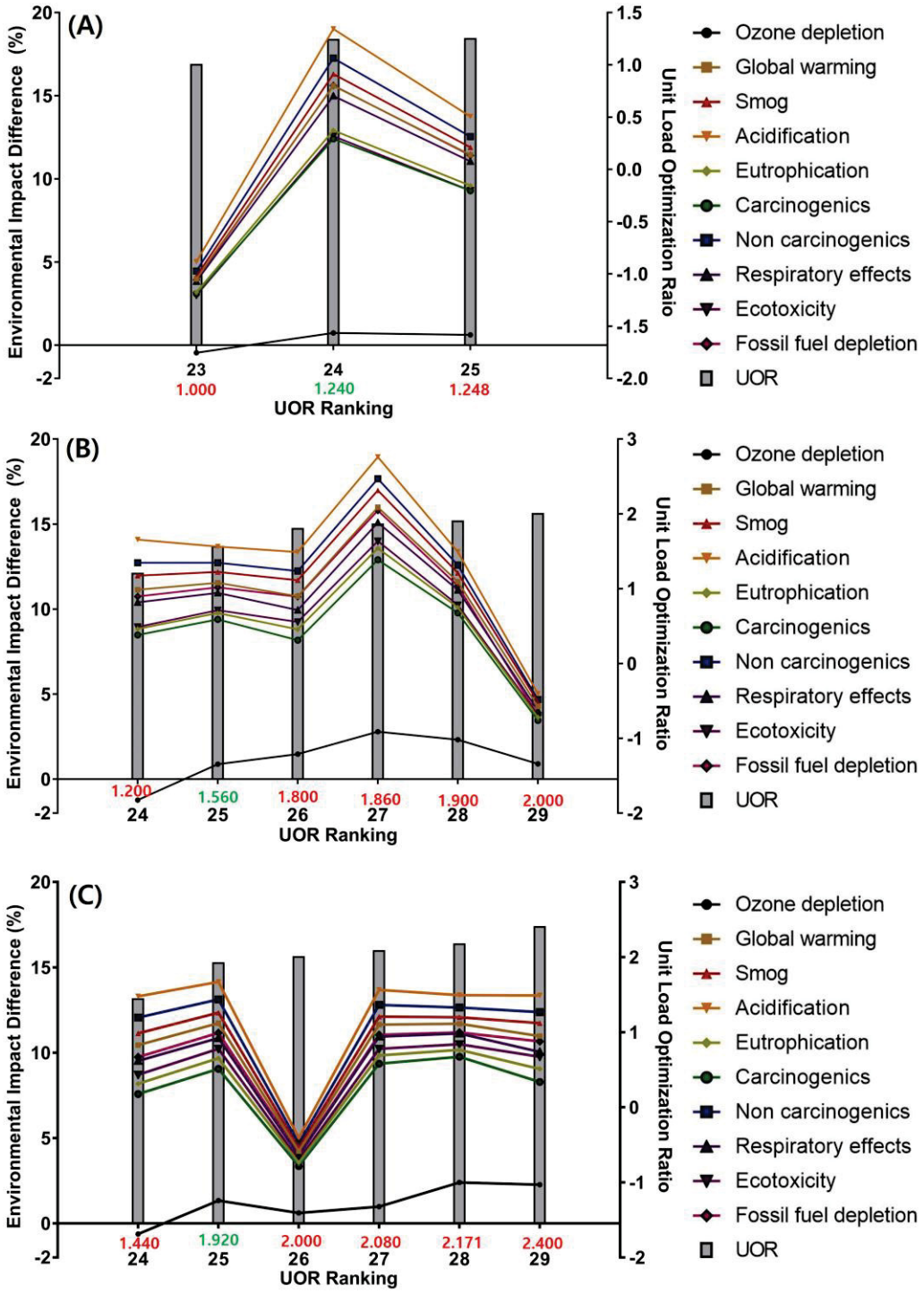

Figure 3.8. Environmental performance difference of unit load scenarios for minimum required condition analysis. (A) shows results for HD HW group, (B) shows results for LD HW group, and (C) shows results for GSYP group.

*Note: Red and green numbers reports UOR of each unit load scenarios. Green numbers especially indicates minimum required condtion of each wood species group.

3.4.4 Sensitivity Analysis Results: Use Transportation

The impact of use transportation distances on the environmental performance of unit load scenarios with minimum required conditions in each wood species group are presented in Figure 3.9. Sensitivity analysis were conducted on unit load scenarios with the minimum required conditions by altering use phase transportation distances since these widely vary depending on the user. Increasing use transportation distance from 100 km to 2,000 km resulted in decreasing environmental benefits from optimizing the unit load design as much as 6.69%, 3.43%, and 3.12% for HD HW group, LD HW group, and GSYP group respectively, in all of the impact categories except for ozone depletion. Ozone depletion did not show notable environmental performance changes nor drop below the environmental performance break-even line for all three wood species groups. Considering ozone depletion as the most closely related impact category for determining the minimum required conditions, from the previous section, none of the impact categories were sufficient to change the environmental status of unit load scenarios with the minimum required conditions. Therefore, these sensitivity analysis results confirmed that the minimum required conditions do not change with different supply chain distance ranges.

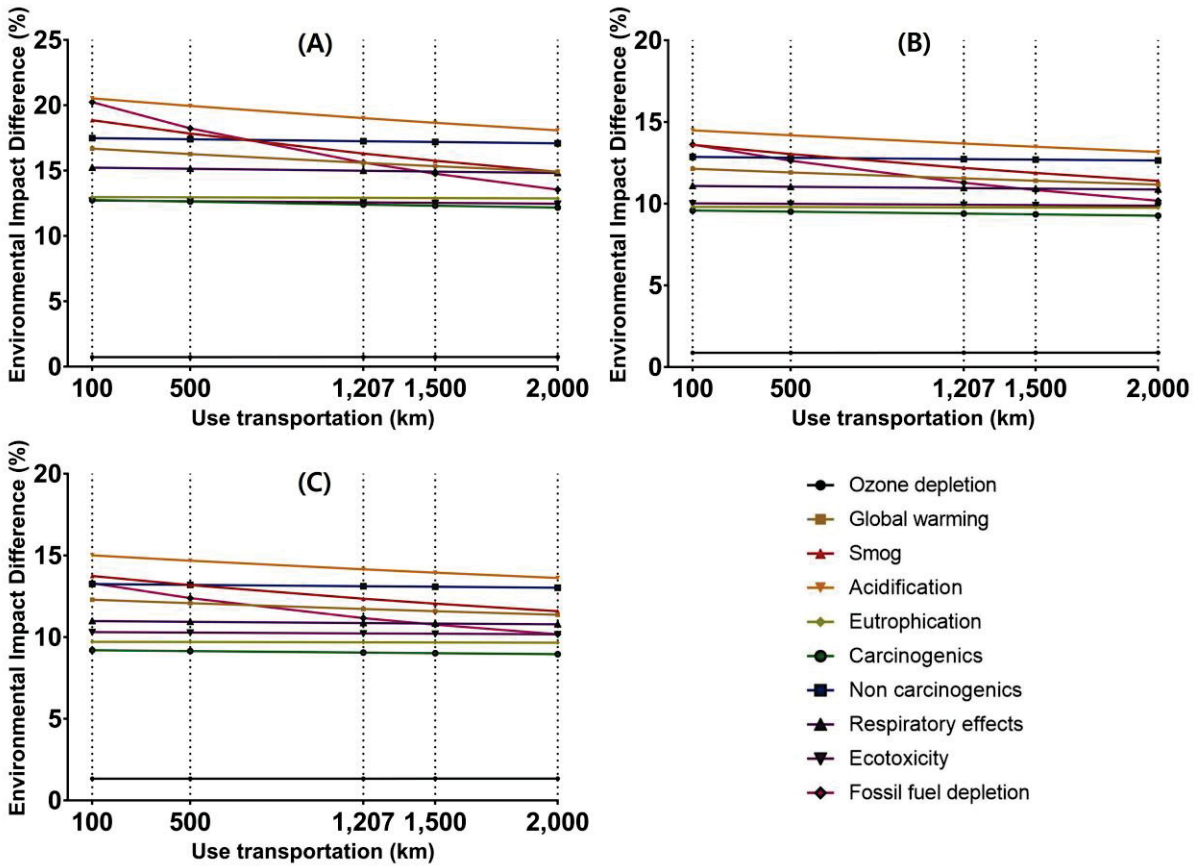

Figure 3.9. Environmental performance change of unit load optimization method as a function of different use phase transportation distances and wood species groups. (A) presents results from HD HW group, (B) presents results from LD HW group, and (C) presents results from GSYP group.

3.5 Assumptions and Limitations

Following assumptions and limitations were made in this study:

1. The modeling of UOR assumed scenarios in which the weight of the pallet was decreasing, and the weight of the corrugated materials was increasing. This model assumes a desire for an optimized unit load on the basis of material use and performance. It is possible that all components could be increased in weight; however, such a design adjustment would contradict the intended objective of optimization.

2. Employed unit load scenarios consisted of 1219.2 mm x 1016 mm GMA style

stringer class wooden pallet and three different sizes of corrugated boxes. Different styles or sizes of pallets and significantly smaller or larger sizes of corrugated boxes than the employed scenarios could affect the results.

3. The wood species were limited to the four main species groups primarily used for pallet manufacturing in the southeastern United States. Different parts of the country use wood species that are easily accessible in their region to build pallets. The use of other wood species will affect the results due to the change in inventory data of pallet raw materials production phase.
4. The LCA did not include the life cycles of the products contained within corrugated boxes and load stabilizers, such as a stretch wrap or band straps, due to their high variability.

3.6 Conclusions

This study was conducted to investigate the environmental performance of the unit load optimization method of increasing top deck board thicknesses and decreasing the board grade of corrugated boxes. Unit load optimization was able to improve the environmental performance of unit load design in many cases as much as 22.93%, 22.85%, 20.48%, and 13.16% for the high-density hardwood group, low-density hardwood group, green southern yellow pine group, and kiln-dried southern yellow pine group, respectively. However, ozone depletion consistently showed a lower performance increase in all wood species groups. It was never able to exceed the environmental performance break-even line for KD SYP group scenarios. This was mainly due to not enough corrugated material decrease compared to pallet material increase since ozone depletion is more heavily affected by the pallet associated factors.

It was also observed that a higher unit load optimization ratio (UOR) does not guarantee higher environmental advantages. There are chances that unit load scenarios with relatively low absolute amount of pallet and corrugated box materials to have higher UOR than unit load scenarios with the relatively high absolute amount of materials used because UOR is only based on the ratio of changes in pallet and corrugated box material utilization. Therefore, it is highly recommended that designers conduct unit load design-

specific environmental analysis in order to understand the actual degree of environmental advantages gained by optimizing a particular unit load scenario.

Minimum required conditions were also investigated as guidance for unit load professionals to estimate whether there is the possibility of environmental benefits through unit load optimization before they proceed to a complete LCA on their specific unit load design. Minimum required UORs for HD HW group, LD HW group, and GSYP group were reported as 1.24, 1.56, and 1.92, respectively. Sensitivity analysis on use phase transportation confirmed that these minimum required UORs remain unchanged even if unit load users have their unique use phase distances. However, it was also emphasized that these values should only be used to support preliminary decision making regarding whether to proceed with further more-complicated analyses due to many other minor factors that could potentially affect them.

These results are significant as they confirm that the unit load optimization method has environmental advantages in many cases. It also allows estimating the minimum conditions that must be present to generate environmentally beneficial and cost-effective unit load designs through the unit load optimization method. This study was the first to suggest to the packaging industry that distribution packaging can be environmentally improved by applying engineering knowledge of physical interactions between different levels of the packaging systems instead of developing a whole new packaging system or material.

3.7 References

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4 Overall Conclusions

This study first investigated the impact of multiple unit load design variables on the unit load design optimization method using physical interactions between pallet top-deck stiffness and corrugated box compression strength. The optimization of the unit load's design was done by reducing the corrugated board grade and increasing the pallet top deck stiffness.

The initial top deck thickness effect and the pallet wood species effect both showed potential to reduce the corrugated board grade by increasing the stiffness of the pallet top deck. When a pallet is initially designed with a stiffer wood species or with a thicker top deckboard, the results showed a significant reduction in the potential of decreasing corrugated board grade by increasing top deck stiffness. Therefore, when the unit load is initially designed with lower stiffness pallets, this evaluated unit load optimization method is more effective. The corrugated box related effects demonstrate that, for boxes with a greater starting board grade, the range of board grade reduction is smaller. The heavier the initial box weights, the more opportunities exist for decreasing board material with only minor changes to top deck thickness.

This study next investigated the environmental performance of the unit load design optimization method of increasing top deck board thickness and decreasing the board grade of corrugated boxes. The optimization of the unit load improved the environmental performance of the unit load design by as much as 22.93%. On the other hand, ozone depletion has consistently led to lower performance increases in all groups of wood species. It was primarily due to insufficient corrugated material decrease as compared to the pallet material increase, as pallet-related factors more heavily influence ozone depletion. It was also discovered that a higher unit load optimization ratio (UOR) does not always imply more significant environmental benefits. Unit load scenarios with lower absolute amounts of pallet and corrugated box materials may have higher UOR than unit load scenarios with higher absolute amounts of materials used. In addition, this study suggested minimum required conditions for unit loads built with different wood species to support preliminary decision making for a unit load specific environmental analysis.

Overall, this study confirmed that the investigated unit load optimization method offers environmental benefits, especially for companies that use low stiffness pallets or have

heavy box unit loads. This was the first study to reveal the impacts of different unit load design factors and to advise enhancing the environmental performance of unit load by using the unit load optimization approach, which is based on the physical interactions between packaging components such as wooden pallets and corrugated boxes.

5 Recommendations for Future Research

Based on the findings and limitations of this study, the following recommendations for further research may be made:

- Investigating the effect of pallet top deck stiffness on package types other than corrugated boxes is recommended.
- Development of a Finite Element Analysis model on the effect of pallet top deck stiffness on corrugated box compression strength is highly recommended.
- Further environmental analysis with more wood species groups from different regions will help increase the generalization of the research findings.
- The environmental performance of the unit load optimization method when pallets are used for international shipping that includes phytosanitary treatments and intermodal transportation modes could be further investigated.
- An additional sensitivity analysis that discovers a single break-even point regarding the transportation factor is also encouraged.

6 Appendix

Appendix A: List of Investigated Unit Load Scenarios with Different Pallet Wood Species.

Table A1. Rank, UOR, and specification of investigated green high-density hardwood unit load scenarios for analysis. Scenarios selected at regular intervals and minimum required condition analysis are highlighted as yellow and green, respectively.

Wood Species	Rank	UOR	Box weight decrease (kg)	Pallet weight increase (kg)	Initial top deck thickness (mm)	Increased top deck thickness (mm)	Initial board grade (kg/mm ECT)	Decreased board grade (kg/mm ECT)	Flute size	Box size
Green High-Density Hardwood	1	0.035	0.73	20.86	15.9	31.8	0.57	0.52	C	Small
	2	0.040	0.44	10.88	9.5	17.5	0.57	0.52	C	Large
	3	0.051	0.87	17.23	12.7	25.4	0.57	0.52	C	Medium
	4	0.114	0.73	6.35	12.7	17.5	0.57	0.52	C	Small
	5	0.137	0.87	6.35	9.5	14.3	0.57	0.52	C	Medium
	6	0.160	0.73	4.54	9.5	12.7	0.57	0.52	C	Small
	7	0.189	2.39	12.70	15.9	25.4	0.91	0.86	BC	Large
	8	0.211	3.63	17.23	19.1	31.8	0.91	0.86	BC	Small
	9	0.218	6.53	29.93	9.5	31.7	0.71	0.57	C	Medium
	10	0.264	2.39	9.07	9.5	15.9	0.91	0.86	BC	Large
	11	0.293	2.39	8.16	12.7	19.1	0.91	0.86	BC	Large
	12	0.320	2.61	8.16	15.9	22.3	0.91	0.86	BC	Medium
	13	0.328	5.66	17.23	12.7	25.4	0.79	0.71	C	Large
	14	0.446	5.66	12.70	9.5	19	0.79	0.71	C	Large
	15	0.576	2.61	4.54	9.5	12.7	0.91	0.86	BC	Medium
	16	0.576	2.61	4.54	12.7	15.9	0.91	0.86	BC	Medium
	17	0.600	6.53	10.88	12.7	20.7	0.79	0.71	C	Medium
	18	0.657	11.32	17.23	12.7	25.4	1.27	1.09	BC	Medium
	19	0.686	8.71	12.70	15.9	25.4	0.79	0.71	C	Small
	20	0.733	7.98	10.88	9.5	17.5	0.71	0.57	C	Small
	21	0.800	3.63	4.54	12.7	15.9	0.91	0.86	BC	Small
	22	0.800	20.32	25.40	12.7	31.8	1.09	0.91	BC	Small
	23	1.000	3.63	3.63	15.9	19.1	0.91	0.86	BC	Small
	24	1.240	13.50	10.88	9.5	17.5	1.09	0.91	BC	Medium
	25	1.248	11.32	9.07	9.5	15.9	1.27	1.09	BC	Medium
	26	1.267	13.79	10.88	12.7	20.7	1.27	1.09	BC	Small
	27	1.333	3.63	2.72	9.5	11.1	0.91	0.86	BC	Small
	28	1.371	8.71	6.35	12.7	17.5	0.79	0.71	C	Small

	29	1.440	6.53	4.54	9.5	12.7	0.79	0.71	C	Medium
	30	1.920	8.71	4.54	9.5	12.7	0.79	0.71	C	Small
	31	2.171	13.79	6.35	9.5	14.3	1.27	1.09	BC	Small
	32	3.200	20.32	6.35	9.5	14.3	1.09	0.91	BC	Small

*Note: Size of small box is 203.2 mm x 304.8 mm x 254 mm, medium box is 406.4 mm x 254 mm x 254 mm, and large box is 609.6 mm x 337.8 mm x 254 mm (Kim et al., 2021).

Table A2. Rank, UOR, and specification of investigated green low-density hardwood unit load scenarios for analysis. Scenarios selected at regular intervals and minimum required condition analysis are highlighted as yellow and green, respectively.

Wood Species	Rank	UOR	Box weight decrease (kg)	Pallet weight increase (kg)	Initial top deck thickness (mm)	Increased top deck thickness (mm)	Initial board grade (kg/mm ECT)	Decreased board grade (kg/mm ECT)	Flute size	Box size
Green Low-Density Hardwood	1	0.021	0.44	20.86	12.7	31.8	0.57	0.52	C	Large
	2	0.040	0.44	10.88	9.5	19	0.57	0.52	C	Large
	3	0.073	0.73	9.98	15.9	25.4	0.57	0.52	C	Small
	4	0.096	0.87	9.07	12.7	20.7	0.57	0.52	C	Medium
	5	0.133	0.73	5.44	12.7	17.5	0.57	0.52	C	Small
	6	0.160	0.87	5.44	9.5	14.3	0.57	0.52	C	Medium
	7	0.192	2.61	13.61	19.1	31.8	0.91	0.86	BC	Medium
	8	0.200	0.73	3.63	9.5	12.7	0.57	0.52	C	Small
	9	0.220	2.39	10.88	9.5	19	0.91	0.86	BC	Large
	10	0.240	2.39	9.98	15.9	25.4	0.91	0.86	BC	Large
	11	0.267	6.53	24.49	9.5	31.7	0.71	0.57	C	Medium
	12	0.330	2.39	7.26	12.7	19.1	0.91	0.86	BC	Large
	13	0.416	5.66	13.61	12.7	25.4	0.79	0.71	C	Large
	14	0.446	5.66	12.70	9.5	20.6	0.79	0.71	C	Large
	15	0.480	2.61	5.44	15.9	20.7	0.91	0.86	BC	Medium
	16	0.647	13.5	20.86	12.7	31.8	1.09	0.91	BC	Medium
	17	0.720	2.61	3.63	9.5	12.7	0.91	0.86	BC	Medium
	18	0.720	2.61	3.63	12.7	15.9	0.91	0.86	BC	Medium
	19	0.900	6.53	7.26	12.7	19.1	0.79	0.71	C	Medium
	20	1.000	3.63	3.63	15.9	19.1	0.91	0.86	BC	Small
	21	1.000	3.63	3.63	19.1	22.3	0.91	0.86	BC	Small
	22	1.040	11.32	10.88	12.7	22.2	1.27	1.09	BC	Medium
	23	1.100	7.98	7.26	9.5	15.9	0.71	0.57	C	Small
	24	1.200	8.71	7.26	15.9	22.3	0.79	0.71	C	Small
	25	1.560	11.32	7.26	9.5	15.9	1.27	1.09	BC	Medium
	26	1.800	6.53	3.63	9.5	12.7	0.79	0.71	C	Medium

27	1.860	13.5	7.26	9.5	15.9	1.09	0.91	BC	Medium
28	1.900	13.79	7.26	12.7	19.1	1.27	1.09	BC	Small
29	2.000	3.63	1.81	9.5	11.1	0.91	0.86	BC	Small
30	2.000	3.63	1.81	12.7	14.3	0.91	0.86	BC	Small
31	2.400	8.71	3.63	9.5	12.7	0.79	0.71	C	Small
32	2.400	8.71	3.63	12.7	15.9	0.79	0.71	C	Small
33	2.533	13.79	5.44	9.5	14.3	1.27	1.09	BC	Small
34	2.800	20.32	7.26	12.7	19.1	1.09	0.91	BC	Small
35	3.733	20.32	5.44	9.5	14.3	1.09	0.91	BC	Small

*Note: Size of small box is 203.2 mm x 304.8 mm x 254 mm, medium box is 406.4 mm x 254 mm x 254 mm, and large box is 609.6 mm x 337.8 mm x 254 mm (Kim et al., 2021).

Table A3. Rank, UOR, and specification of investigated green southern yellow pine unit load scenarios for analysis. Scenarios selected at regular intervals and minimum required condition analysis are highlighted as yellow and green, respectively.

Wood Species	Rank	UOR	Box weight decrease (kg)	Pallet weight increase (kg)	Initial top deck thickness (mm)	Increased top deck thickness (mm)	Initial board grade (kg/mm ECT)	Decreased board grade (kg/mm ECT)	Flute size	Box size
Green Southern Yellow Pine	1	0.023	0.44	19.05	12.7	31.8	0.57	0.52	C	Large
	2	0.048	0.44	9.07	9.5	19	0.57	0.52	C	Large
	3	0.107	0.87	8.16	12.7	20.7	0.57	0.52	C	Medium
	4	0.114	0.73	6.35	12.7	19.1	0.57	0.52	C	Small
	5	0.192	0.87	4.54	9.5	14.3	0.57	0.52	C	Medium
	6	0.206	2.61	12.70	19.1	31.8	0.91	0.86	BC	Medium
	7	0.240	2.39	9.98	15.9	25.4	0.91	0.86	BC	Large
	8	0.267	0.73	2.72	9.5	12.7	0.57	0.52	C	Small
	9	0.330	2.39	7.26	9.5	17.5	0.91	0.86	BC	Large
	10	0.377	2.39	6.35	12.7	19.1	0.91	0.86	BC	Large
	11	0.400	6.53	16.33	15.9	31.8	0.79	0.71	C	Medium
	12	0.446	5.66	12.70	12.7	25.4	0.79	0.71	C	Large
	13	0.480	2.61	5.44	15.9	20.7	0.91	0.86	BC	Medium
	14	0.520	5.66	10.88	9.5	20.6	0.79	0.71	C	Large
	15	0.554	6.53	11.79	9.5	22.2	0.71	0.57	C	Medium
	16	0.571	3.63	6.35	19.1	25.5	0.91	0.86	BC	Small
	17	0.709	13.5	19.05	12.7	31.8	1.09	0.91	BC	Medium
	18	0.844	13.79	16.33	15.9	31.8	1.27	1.09	BC	Small
	19	0.873	8.71	9.98	15.9	25.4	0.79	0.71	C	Small
	20	0.960	2.61	2.72	12.7	15.9	0.91	0.86	BC	Medium
	21	1.000	3.63	3.63	15.9	19.1	0.91	0.86	BC	Small

22	1.100	7.98	7.26	9.5	17.5	0.71	0.57	C	Small
23	1.387	11.32	8.16	12.7	20.7	1.27	1.09	BC	Medium
24	1.440	6.53	4.54	12.7	17.5	0.79	0.71	C	Medium
25	1.920	8.71	4.54	12.7	17.5	0.79	0.71	C	Small
26	2.000	3.63	1.81	12.7	14.3	0.91	0.86	BC	Small
27	2.080	11.32	5.44	9.5	15.9	1.27	1.09	BC	Medium
28	2.171	13.79	6.35	12.7	19.1	1.27	1.09	BC	Small
29	2.400	6.53	2.72	9.5	12.7	0.79	0.71	C	Medium
30	2.480	13.5	5.44	9.5	15.9	1.09	0.91	BC	Medium
31	2.880	2.61	0.91	9.5	11.1	0.91	0.86	BC	Medium
32	3.040	13.79	4.54	9.5	14.3	1.27	1.09	BC	Small
33	3.200	8.71	2.72	12.7	19.1	1.09	0.91	BC	Small
34	3.200	20.32	6.35	9.5	12.7	0.79	0.71	C	Small
35	4.000	3.63	0.91	9.5	11.1	0.91	0.86	BC	Small
36	4.480	20.32	4.54	9.5	14.3	1.09	0.91	BC	Small

*Note: Size of small box is 203.2 mm x 304.8 mm x 254 mm, medium box is 406.4 mm x 254 mm x 254 mm, and large box is 609.6 mm x 337.8 mm x 254 mm (Kim et al., 2021).

Table A4. Rank, UOR, and specification of investigated kiln-dried southern yellow pine unit load scenarios for analysis. Scenarios selected at regular intervals are highlighted.

Wood Species	Rank	UOR	Box weight decrease (kg)	Pallet weight increase (kg)	Initial top deck thickness (mm)	Increased top deck thickness (mm)	Initial board grade (kg/mm ECT)	Decreased board grade (kg/mm ECT)	Flute size	Box size
Kiln-dried Southern Yellow Pine	1	0.16	0.73	4.54	11.1	28.6	0.57	0.52	C	Small
	2	0.527	2.39	4.54	11.1	28.6	1.27	1.09	BC	Large
	3	0.575	2.61	4.54	11.1	28.6	1.27	1.09	BC	Medium
	4	0.799	3.63	4.54	11.1	28.6	1.27	1.09	BC	Small
	5	1.918	8.71	4.54	11.1	28.6	0.79	0.71	C	Small

*Note: Size of small box is 203.2 mm x 304.8 mm x 254 mm, medium box is 406.4 mm x 254 mm x 254 mm, and large box is 609.6 mm x 337.8 mm x 254 mm (Kim et al., 2021).

Appendix B: Input and outputs for the raw material production of different wood species groups.

Table B1. Inputs and outputs for the raw material production of 1 kg of wooden pallet built with green high-density hardwood (modified from Alanya-Rosenbaum et al. (2021)).

	Unit	Weighted average	Allocation (%)
Outputs: Products/Coproducts			
Wood board	kg	1	82.3
Sawdust	kg	0.083	6.8

Hogged material	kg	0.052	4.3
Wood chips	kg	0.063	5.2
Scrap wood	kg	0.0006	0.05
Shavings	kg	0.016	1.35
Inputs: materials/fuels			
Sawn lumber, softwood, rough, green, at sawmill, SE/m3/RNA	m3	1.40E-03	
Greases	g	1.78E+00	
Motor oil	g	5.17E+00	
Hydraulic fluid	g	1.08E+01	
Lubricating fluid	g	7.17E+00	
Plastic wrapping	g	4.55E+00	
Cardboard packaging	g	3.42E+00	
Natural gas	L	1.88E+02	
Diesel	L	5.41E-01	
Gasoline	L	5.50E-03	
Liquefied petroleum gas	L	2.48E-02	
Wood fuel	OD kg	1.40E-02	
Diesel, forklift	L	1.67E-01	
Diesel, truck	L	7.37E-02	
Gasoline, truck	L	7.49E-04	
Propane, forklift	L	5.31E-01	
Inputs: electricity/heat			
Electricity, at grid, SERC, 2010/kWh/RNA	kWh	0.002	
Outputs: Waste/emissions to treatment			
Steel scrap	g	2.99E+02	
Plastic wrap	g	6.99E+00	
Cardboard packaging	g	7.60E+01	
Hydraulic fluid	g	1.14E+00	
Motor oil	g	1.67E-01	
Greases	g	3.04E-02	
Lubricants	g	1.49E+01	

Table B2. Inputs and outputs for the raw material production of 1 kg of wooden pallet built with green low-density hardwood (modified from Alanya-Rosenbaum et al. (2021)).

	Unit	Weighted average	Allocation (%)
Outputs: Products/Coproducts			
Wood board	kg	1	82.3
Sawdust	kg	0.083	6.8

Hogged material	kg	0.052	4.3
Wood chips	kg	0.063	5.2
Scrap wood	kg	0.0006	0.05
Shavings	kg	0.016	1.35
Inputs: materials/fuels			
Sawn lumber, softwood, rough, green, at sawmill, SE/m3/RNA	m3	1.70E-03	
Greases	g	2.16E+00	
Motor oil	g	6.28E+00	
Hydraulic fluid	g	1.31E+01	
Lubricating fluid	g	8.71E+00	
Plastic wrapping	g	5.52E+00	
Cardboard packaging	g	4.15E+00	
Natural gas	L	2.29E+02	
Diesel	L	6.57E-01	
Gasoline	L	6.68E-03	
Liquefied petroleum gas	L	3.01E-02	
Wood fuel	OD kg	1.70E-02	
Diesel, forklift	L	2.03E-01	
Diesel, truck	L	8.95E-02	
Gasoline, truck	L	9.10E-04	
Propane, forklift	L	6.44E-01	
Inputs: electricity/heat			
Electricity, at grid, SERC, 2010/kWh/RNA	kWh	0.003	
Outputs: Waste/emissions to treatment			
Steel scrap	g	3.63E+02	
Plastic wrap	g	8.49E+00	
Cardboard packaging	g	9.23E+01	
Hydraulic fluid	g	1.38E+00	
Motor oil	g	2.03E-01	
Greases	g	3.69E-02	
Lubricants	g	1.81E+01	

Table B3. Inputs and outputs for the raw material production of 1 kg of wooden pallet built with green southern yellow pine (modified from Alanya-Rosenbaum et al. (2021)).

	Unit	Weighted average	Allocation (%)
Outputs: Products/Coproducts			
Wood board	kg	1	82.3
Sawdust	kg	0.083	6.8

Hogged material	kg	0.052	4.3
Wood chips	kg	0.063	5.2
Scrap wood	kg	0.0006	0.05
Shavings	kg	0.016	1.35
Inputs: materials/fuels			
Sawn lumber, softwood, rough, green, at sawmill, SE/m3/RNA	m3	0.0019	
Greases	g	2.41E+00	
Motor oil	g	7.01E+00	
Hydraulic fluid	g	1.47E+01	
Lubricating fluid	g	9.74E+00	
Plastic wrapping	g	6.17E+00	
Cardboard packaging	g	4.64E+00	
Natural gas	L	2.56E+02	
Diesel	L	7.34E-01	
Gasoline	L	7.47E-03	
Liquefied petroleum gas	L	3.36E-02	
Wood fuel	OD kg	1.90E-02	
Diesel, forklift	L	2.27E-01	
Diesel, truck	L	1.00E-01	
Gasoline, truck	L	1.02E-03	
Propane, forklift	L	7.20E-01	
Inputs: electricity/heat			
Electricity, at grid, SERC, 2010/kWh/RNA	kWh	0.003	
Outputs: Waste/emissions to treatment			
Steel scrap	g	4.06E+02	
Plastic wrap	g	9.49E+00	
Cardboard packaging	g	1.03E+02	
Hydraulic fluid	g	1.55E+00	
Motor oil	g	2.27E-01	
Greases	g	4.13E-02	
Lubricants	g	2.02E+01	

Table B4. Inputs and outputs for the raw material production of 1 kg of wooden pallet built with kiln-dried southern yellow pine (modified from Alanya-Rosenbaum et al. (2021)).

	Unit	Weighted average	Allocation (%)
Outputs: Products/Coproducts			
Wood board	kg	1	82.3

Sawdust	kg	0.083	6.8
Hogged material	kg	0.052	4.3
Wood chips	kg	0.063	5.2
Scrap wood	kg	0.0006	0.05
Shavings	kg	0.016	1.35
Inputs: materials/fuels			
Sawn lumber, softwood, planed, kiln dried, at planer, SE/m3/RNA	m3	0.0023	
Greases	g	2.92E+00	
Motor oil	g	8.49E+00	
Hydraulic fluid	g	1.78E+01	
Lubricating fluid	g	1.18E+01	
Plastic wrapping	g	7.47E+00	
Cardboard packaging	g	5.62E+00	
Natural gas	L	3.10E+02	
Diesel	L	8.89E-01	
Gasoline	L	9.04E-03	
Liquefied petroleum gas	L	4.07E-02	
Wood fuel	OD kg	2.30E-02	
Diesel, forklift	L	2.75E-01	
Diesel, truck	L	1.21E-01	
Gasoline, truck	L	1.23E-03	
Propane, forklift	L	8.72E-01	
Inputs: electricity/heat			
Electricity, at grid, SERC, 2010/kWh/RNA	kWh	0.004	
Outputs: Waste/emissions to treatment			
Steel scrap	g	4.91E+02	
Plastic wrap	g	1.15E+01	
Cardboard packaging	g	1.25E+02	
Hydraulic fluid	g	1.87E+00	
Motor oil	g	2.75E-01	
Greases	g	4.99E-02	
Lubricants	g	2.45E+01	