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Environmental impact analysis of alternative pallet management systems

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I DEDICATE THIS WORK

TO MY PARENTS KARL AND MAITE

FOR THEIR UNCONDITIONAL LOVE AND SUPPORT,

FOR BEING AN EXAMPLE TO FOLLOW

AND GUIDING ME THROUGH MY PERSONAL AND PROFESSIONAL CAREER.

TO MY BROTHERS ANDONI AND UNAI

FOR CONTINUOUSLY FULFILLING MY HEART WITH LOVE, HAPPINESS

AND STRENGTH TO PURSUE MY GOALS.

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Disclaimer

The models developed in this thesis could only be analyzed by invoking the very specific structural and contextual assumptions that are described in the body of the work. The findings that arise from the study of these models and the conclusions that are developed from these findings are, by extension, also heavily dependent upon the assumptions invoked. Extrapolation of these findings to environments where the modeling assumptions do not hold will likely yield unsupportable results, and is not encouraged.

ABSTRACT

Pallets, the most common unit-load platform, allow the transportation of goods in an efficient and reliable way. Every year, 700 million new pallets are manufactured and become part of the approximately 2 billion pallets that are in circulation in the U.S. The total life-cycle environmental impact of pallets depends on materials, manufacturing, handling processes, and the disposal practice (end-of-life). Plastic pallets can be lighter and might last longer but their manufacturing processes are energy intensive and could contribute significantly to greenhouse gas (GHG) emissions. On the other hand, wooden pallets can be cheaper and easily repaired but present a shorter life. The ability to control the end-of-life of the pallets and the associated environmental impacts of each scenario allows pallet pooling service companies to provide logistics arrangements that are attractive to those companies seeking to better manage their carbon footprint. The appropriate choice of pallet type (i.e. material, durability, etc.) and management structure (e.g. cost, lease vs. buy, etc.) may lead to a more sustainable logistics operation. The purpose of this study is to provide a model that would determine the impact of pallet materials, manufacturing, distribution, and take back operations on an environmental performance metric (such as carbon dioxide emissions) as well as cost. Mixed integer programming (a minimum cost multi-commodity network flow problem) is used to design the system that determines the mix of pallets (type, quantity, and pallet management system) for product distribution that balances overall environmental impacts and costs according to companies' needs. Such a tool would aid in decision making at the logistics and distribution levels. Results from a case study of a large grocery distributor/retailer in the Northeast is presented.

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INTRODUCTION

Supply chains are growing more and more complex. This is due to many factors, including the expansion of global markets and product SKUs (stock-keeping units), an increased variety of shipping and distribution modes, and rising expectations from customers, particularly with respect to service levels and delivery times. At the same time, companies are striving to make their supply chains more efficient and more sustainable. For example, Walmart in the U.K. makes continuously improvements in their fleets to reduce their energy and carbon footprint. Asquith and Dairies (ASDA) (subsidiary of Walmart) delivered more than 40 million more cases/containers in 2009 than in 2008 while eliminating almost 9 million miles. Their fleet efficiency improvement from 2005 to 2009 allowed them to avoid emitting more than 81,000 metric tons of CO_2 in 2009. In addition, other efforts of product distributor's are focused on being supplied 100 percent by renewable energies while installing solar panel power projects and purchasing electricity generated by renewable sources, and in eliminating waste from stores by improving their recycling and waste redirection efforts (Walmart, 2010).

One way to make a company's supply chain more competitive and sustainable is to evaluate their shipping and distribution operations. Pallets, being the most common unit load platform for handling and storing goods, are a critical component of these operations. Because many pallets are used when producing and distributing large quantities, the environmental impacts associated with the use of a single pallet are greatly multiplied.

Pallets, the most common unit-load platform, allow the transportation of goods in an efficient, reliable, and seamless way. It is estimated that 80 percent of U.S. trade is carried on pallets (Raballan & Aldaz-Carroll, 2005). Every year, 700 million new pallets are manufactured and become part of the large pool (roughly 2 billion) of pallets that are in circulation in the U.S. (Grande, 2008). In the European Union

some 280 million pallets are in circulation every year. Many of these pallets are used only a few times and end up meeting one of the end-of-life scenarios (e.g. landfill, municipal incineration, or downcycling) while others are repaired and reused many times. As companies set goals to become more sustainable, a thorough understanding of the environmental impacts of their operations becomes critical.

The life-cycle environmental impact of pallets depends on materials, manufacturing, handling processes, and the disposal practice (end-of-life). The embodied energies[1] for the raw materials generally used to make pallets vary. High-density polyethylene (HDPE) has an embodied energy of 8320 to 9200 kcal/lb., while the embodied energy of hardwood oak ranges from 780 to 862 kcal/lb. The subsequent processing of the raw materials to fashion them into pallets also consumes energy and, therefore, adds to the embodied energy of the finished pallets. Plastic pallets might be lighter and last longer, but their manufacturing processes are energy intensive and perhaps contribute significantly to greenhouse gas (GHG) emissions. On the other hand, wood pallets are cheaper and easily repaired but present a shorter life.

Once a pallet has been used for the distribution of consumer products they may experience different end-of-life scenarios. The scenarios include reuse, remanufacture (repair in pallets context), materials recycling, incineration, and landfilling. A high percentage of damaged wooden pallets are repaired; while others are recycled. Recycling of wood from pallets is really a downcycling step. The material is chipped and ground to produce either landscape mulch or animal bedding, which allows for waste reduction and adds another lifecycle to the materials. Other disposal scenarios for wooden pallets include landfilling or incineration depending on the local practices and regulations. When plastic pallets get damaged, they are shredded and the resulting plastic is recycled to make either new pallets or other plastic products. The structural metal components usually found in plastic pallets are also recycled. Typically, plastic pallets are

[1] The embodied energy of a material is the energy required to produce a unit of that material from its raw material ores and feedstocks. Embodied energy is usually described in terms of energy content per unit weight (eg. kcal/lb or MJ/kg) (CES, 2010)

not repaired. All these scenarios and practices offset or produce different levels of GHG emissions and will consequently impact the environment.

Product transportation also negatively impacts the environment. The Department of Transportation (BTS, 2009) estimates that transportation represents roughly 10 percent of the U.S. gross domestic product, or approximately $1.4 trillion. In 2006, there were 8.8 million trucks that traveled approximately 263 billion miles. Freight, in its many forms, accounts for 470 million metric tons of carbon dioxide equivalent annually (7.8 percent of total U.S. CO_2 emissions), and it contributes about 50 percent of NO_x emissions and 40 percent of particulate matter emissions from transportation sources (EPA, 2006; FHA, 2010). Truck freight accounts for 70 percent of all these emissions. Pallets are indirectly responsible for a share of the emissions that are generated as the pallets and their cargo move through the supply chain. Primary freight transportation methods (ship, rail, air, and truck) are all fossil fuel based, and heavier pallets will require more fuel to transport them than lighter pallets. In addition to the product shipping operation, the pallet take back logistics produces CO_2, SO_x, NO_x, and particular matter emissions. Therefore, pallet management systems may dramatically affect the environmental impacts arising from the operation of product transportation and delivery systems.

The ability to control the end-of-life of the pallets and the associated environmental impacts of each scenario allows pallet pooling service companies to provide logistics arrangements that are attractive to companies seeking to manage their carbon footprint. However, the complexities of today's supply chains and the breadth of environmental impacts pose a challenge to those seeking to engage in sustainable practices. The challenges will lie on selecting the appropriate pallet type (i.e. material, durability, etc.) and management structure (e.g. cost, lease vs. buy, etc.) while keeping other aspects in consideration (e.g. toxicity, etc.).

This research addresses the two attributes of a pallet that determine much of its cost and environmental impact: (*i*) how it is managed and, (*ii*) what it is made of. A proposed method for choosing these

attributes in a way that balances the tradeoffs between cost and an environmental performance metric such as carbon dioxide emissions is explained in detail. Such a tool can aid in decision making at the logistics and distribution level, which will determine the optimal mix of pallets (quantity, material, and pallet management system) to be delivered among facilities, in order to reduce the use of resources, transportation and thus, fuel emissions. Consequently, this will create a better management of resources and material flow system while cutting down the cost of logistics.

Mathematical programming is used to design the system that yields the lowest levels of environmental impacts (such as CO_2 emissions) resulting from pallet materials, manufacturing, distribution, and take back operations, while reducing costs.

A case study from a large grocery distributor/retailer in the Northeast is presented. Pallet providers supply pallets to consumer product manufacturers to transport their products through product distributor's facilities. The grocery distributor/retailer owns 8 distribution centers, 75 stores, and a single return center.

CHAPTER I

BACKGROUND INFORMATION

This chapter provides information on pallet designs, materials, manufacturing processes, sustainable development, life cycle assessment, and pallet management.

1.1 PALLET INDUSTRY

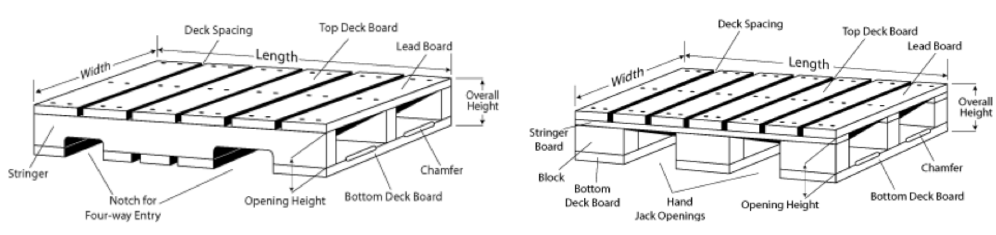
Pallets are rigid horizontal platforms for unit load formation that are easily portable by special material handling equipment. They serve for storing, stacking, handling, and transporting goods as a unit load (http://www.mhia.org/industrygroups/rpcpa). A unit load describes "a single item, a number of items, or a bulk material, that is arranged and restrained so that the load can be stored, picked up, and moved between two locations as a single mass" (White & Hamner, 2005). Pallets allow reducing handling costs and avoid the use of other more expensive devices to lift products.

Different materials are used for the production of pallets, such as wood, corrugated cardboard, plastic, metal, and hybrid composites. In the U.S. an estimated 500 million new pallets were produced in 2006, from which approximately 441 million were made of wood. Other materials, such as plastics (8.3 million) are usually used to conform with sanitary regulations in the grocery industry; while metals (1.1 million) are used in closed-loop material systems for their durability (Bush & Araman, 2009; White, 2004). They all present different characteristics with respect to cost, durability, weight, sanitization and decontamination, load rating, stackability, and tolerance for abuse.

1.1.1 PALLET DESIGN

Pallets may be either reusable (also called nonexpendable or multi-use) or expendable (single-use, one-way or limit-use). *Reusable pallets* are built for strength and durability, and are designed for prolonged use. These types of pallets are made of metal, plastic, or wood (mainly hardwood). Reusable wood pallets are often made from thicker, more durable wood and are frequently purchased for warehouse or factory use. *Expendable pallets* are generally used in shipping and transportation when the shipper does not expect to have the pallets returned. Expendable wood pallets are generally built from lighter, less expensive wood, as low grade softwood, and are designed for a limited number of uses (McKeever et al., 1982).

With respect to its design, pallets can be categorized as stringer pallets or block pallets (refer to Figure 1). *Stringer pallets* use a frame of three parallel pieces called stringers. The deckboards are then placed at right angles to the stringers to create the loading platform. The deckboards comprise the top and bottom exterior of a pallet. The term bottom deck is usually used for the arrangement of deckboards that make up the lower, load-bearing surface of the pallet. When a pallet has both, the upper and lower deckboards, it is called a *reversible or double faced pallet*; if it only has the upper deck it is known as *non-reversible or single faced pallet*. *Block pallets* are typically stronger than stringer pallets. Block pallets utilize both parallel and perpendicular stringers to better facilitate efficient handling. A stringerboard is a component of a pallet that is a solid board placed between the deckboard and the block and extending the full length of a block pallet.



(a) Stringer Pallet **(b) Block Pallet**

Figure 1. Type of pallet according to its structure (http://www.gmpallet.com)

Pallets can be "*two-way entry*" or "*four-way entry*" pallets, allowing two or four sides' insertion of forks. Pallets have different names depending on the construction of the decks and stringers. A *flush pallet* is a pallet constructed in such a manner that there are no overhangs and the decks, both top and bottom, fit 'flush' with the stringers on all sides. A *single wing pallet* is a pallet whose top deckboards extend beyond the edges of the stringers and whose bottom deckboards are flush. A *double wing pallet* is a pallet constructed in such a way as to have the top deck extending out from opposite sides (http://www.wikimheda.org). The reusable stringer pallet is the most used in the U.S., representing 41.9 percent of total pallet production for 2006 (Bush & Araman, 2009).

Approximately 2 billion pallets are in use at any moment in the U.S. (NWPCA, 1999). Most of those pallets are designed to meet the specific performance requirements of the customer. There are more than 400 different pallet sizes. In 1976, the Grocery Pallet Council and Canadian Pallet Council introduced the first pallet standard, now called the Grocery Manufacturers Association or "GMA" specification. The standard footprint, 48 inches long (stringer length) and 40 inches wide (deckboard length) (known as 48x40) was developed to improve the supply chain operations while reducing the costs associated with multiple pallet specifications (Ray, 2007 presented in (IFCO, 2009)). This pallet is usually 5 inches high. Today, the GMA pallet size is the most common standard size in the U.S., which accounts for approximately 26.9 percent of all new wood pallets produced in the U.S. (Bush & Araman, 2009). In Europe the most widely used pallet size is 1200x800mm^2 (called Euro pallet) and in Asia the 1100x1100mm^2 (Buehlmann et al., 2009).

1.1.2 Pallet Materials

Wooden pallets are made of either softwood (spruce, pine, douglas-fir, among other species) or hardwood (oak, maple, or mixed hardwoods); with the Oak species group being the predominant one

within hardwoods (22.4 percent) and the Southern Pine species group within the softwoods (7.1 percent) (Bush & Araman, 2009). Wooden pallets can be cheap and easily reparable. A high percentage is made of lumber that is left over from buildings materials and furniture (NWPCA, 2008). Depending on their structure they can last from 4 to 30 trips, assuming 8 handlings per trip, which gives an estimated service life of 0.5 to 1.5 years (Brindley, 2010). A wood pallet can greatly vary in weight depending on the type of wood and structure used. Typically they range between 40 and 90 pounds per pallet (E. Deomano, personal communication, July 15, 2009).

Plastic pallets are mainly made of polyethylene, either new HDPE (high-density polyethylene) or recycled PET (polyethylene terephthalate) (PCRS, 2000; White, 2004). They are usually stackable and durable, lasting between 60 and 250 trips (Brindley, 2010; Pearson, 2009). They resist weathering, chemicals, and corrosion, and can weigh between 12 and 75 pounds a pallet depending on their structure and manufacturing process (Grande, 2008). A plastic pallet's life service varies from 5 to 10 years, or sometimes even longer, depending on the handling systems used along their useful life.

Metal pallets are strong and the most durable. They are used for heavy loads and loads moved by abrupt logistic systems. They are bug free and sanitary. Materials for metal pallets manufacture include carbon steel, stainless steel, and aluminum. Carbon steel offers high durability at the lowest cost, although it is susceptible to rusting. Stainless steel advantage is that it does not require a paint coating. Aluminum is extremely lightweight in relation to its strength; it is an inert material that is not combustible and poses no health risks. Metal pallets can weigh between 40 and 160 pounds a pallet and their service life varies from 9 to 15 years. Stainless steel and aluminum pallets are the most expensive pallets. They can cost from 2 to 3 times more than pallets made of wood, plastic, and even carbon steel.

The typical wood pallet is manufactured by first cutting the lumber (softwood or hardwood) to length, and then ripping the short lumber into pallet parts; stringers are notched and assembled using nailing machines. New wood pallets are built from the downfall that is left over from producing building

materials and furniture; rarely are trees cut down to make pallets (National Solid Waste Management Association presented in (IFCO, 2009)).

The tradeoff between cost and durability of pallets greatly influences the choice of pallet material. In one report by the World Bank (Raballan & Aldaz-Carroll, 2005), the costs per trip (one pickup/drop-off cycle with significant travel in between) were summarized for a few materials:

Table 1. Pallet costs per trip in various materials (Raballan & Aldaz-Carroll, 2005)

	Hardwood	Softwood	Plastic
Cost (new)	$9.00	$6.00	$60.00
Cost (rebuilt)	$6.00	N/A	N/A
Estimated life	25 trips	2 trips	100 trips
Cost per trip	$0.36	$3.00	$0.60

Although the analysis presented in Table 1 is based on assumptions, the deductions are nonetheless the same: softwood pallets can be inexpensive but only last a few trips and may not be worth repairing, whereas plastic pallets can last a long time but their cost is significantly higher; while the cost and durability of hardwood pallets fall in between that of softwood and plastic (but they are typically repaired).

1.1.3 Pallet Manufacturing and End-of-Life Scenarios

The manufacturing process for plastic pallets is typically more energy intensive than for wood pallets. The production of a common 48x40 plastic pallet can consume up to 8 times more raw material, and up to 5 times more energy to source, process and manufacture, than a comparable reusable wood pallet (Lacefield, 2008). Injection molding and thermoforming are the dominant processing methods for manufacturing plastic pallets; other include structural foam molding, rotomolding, and compression

molding (Grande, 2008). Each of the five main processes used to make pallets has its own advantages in terms of productivity, performance, and end-use application. For the process of *injection molding*, plastic gets injected, under pressure, into a closed cavity mold, and then the material is cooled to ensure that it maintains the exact shape of the mold. This process produces a solid wall, solid core part. These pallets weigh approximately 40 pounds. *Thermoforming* can be single sheet or twin sheet. In single sheet thermoforming, a sheet of plastic is heated and then drawn by vacuum over a mold. In twin sheet thermoforming, two sheets of plastic are heated and drawn by vacuum over separate molds and then fused together through pressure to form a structural double walled part. Pallets made by thermoforming are impact resistant and have an average weight of 20 and 30 pounds; they are commonly used in the grocery industry and in distribution services. In *structural foam molding* plastic and nitrogen gas are injected into a closed cavity mold, which gets cooled to create the exact shape of the mold. The combined use of these materials creates a cellular core that forms a solid skin. These pallets weigh 40 pounds on average and have superior static load capacity for racking, distribution, and stacking. They are commonly used in the automotive industry. *Rotomolding* is typically used for large, custom, heavy-duty pallets for conveyor systems, food processing, and warehouse storage. It offers low-cost tooling but cycle times are longer. *Compression molding* has emerged as an attractive method that can handle the variable processing characteristics of recycled resins. Other manufacturing processes are blow molding and profile extrusion (PCRS, 2003; White, 2004; http://plasticpallet.com).

Some wooden pallets are repaired when damaged. A damaged pallet is disassembled and broken parts are removed. Broken components are replaced. Severely damaged pallets are ground up for mulch, shredded for animal bedding, furnished for fiber-based products, or used as energy fuel. Stringers can be repaired using metal connector plates (NWPCA, 2008).

When plastic pallets get damaged, they get ground down (recycled), and the resulting plastic is reused to make new pallets or used for other applications. The attrition rate of plastic pallets is considered to be very low; for example, only 0.003 percent of a total of 2 million pallets handled by iGPS (Intelligent

Global Pooling Systems) in 2008, which only represents 60 pallets, got damaged and required recycling (Lacefield, 2008).

1.1.4 EMBODIED ENERGY, SANITATION AND STERILIZATION

The embodied energy of a material is the energy required to produce a unit of that material from its raw material ores and feedstocks. Embodied energy is usually described in terms of energy content per unit weight (eg. kcal/lb or MJ/kg). This metric is useful in distinguishing materials that can be synthesized without the investment of large amounts of energy (e.g. the embodied energy of cast iron ranges from 1.78-1.97 kcal/lb) from those that are very energy intensive (e.g. the embodied energy of platinum is about 12,400,000 kcal/lb) (CES, 2010).

The embodied energies for the raw materials generally used to make pallets vary. High-density polyethylene (HDPE) has an embodied energy of 8320 to 9200 kcal/lb., while the embodied energy of oak (a hardwood used to make durable wood pallets) ranges from 780 to 862 kcal/lb. The subsequent processing of the raw materials to fashion them into pallets also consumes energy and therefore adds to the embodied energy of the finished pallets. Processing HDPE pellets into pallets will require an energy intensive polymer injection molding process (665-735 kcal/lb) or other thermoforming operation (e.g. polymer extrusion 262-289 kcal/lb), while transforming oak boards merely requires simple cutting and assembly which can be done without the investment of much new energy (51.5-56.9 kcal/lb). The material recycling energy is approximately 2880-3190 kcal/lb for HDPE. Both wood and plastic can be combusted for energy recovery with the net heat of combustion being 4760-5010 kcal/lb for HDPE and 2140-2310 kcal/lb for oak (CES, 2010).

Pallets made of raw, untreated wood are required to comply with ISPM 15, which is an International Standard for Phytosanitary Measure imposed by the International Plant Protection Convention (IPPC,

2009)[2] that addresses the treatment of wooden pallets used to ship products between countries for them to get incapable of being a carrier of invasive species of insects and plant diseases. Pallets get treated by either of the following means under the supervision of an approved agency: heat treatment, or chemical fumigation. Pallets made of non-wood materials such as steel, aluminum, plastic, or engineered wood products, such as plywood, oriented strand board, or cardboard do not need IPPC approval (http://www.atafreight.com).

During *heat treatment*, wooden pallets are heat treated until the core temperature of the pallet reaches a minimum temperature of 56 °C (132.8 °F) for at least 30 minutes. During *fumigation*, pallets may be treated with methyl bromide according to a schedule that achieves a specified minimum concentration-time product (CT) over 24 hours at temperatures and final residual concentrations as specified. Note that there may be important environmental impacts to consider with either approach (heat treatment and fumigation). Certainly, energy will be required to elevate the temperature of pallets to 56 °C (133 °F) for those pallets that undergo heat treatment, and will therefore increase the embodied energy of pallets so treated. Increasing the embodied energy of pallets is not the only environmental impact that can arise from sanitation measures. ISPM sanctions fumigation with methyl bromide as a sanitary measure. When used as a fumigant, methyl bromide gas is injected into a chamber or under a tarp containing the material to be sterilized. About 80 percent to 95 percent of the methyl bromide used for a typical treatment eventually enters the atmosphere (EPA, 2010; MBAO, 2010). Methyl bromide is known to be an ozone depleting material with an ozone depleting potential in the range between 0.2 and 0.5 (EPA, 2010). Furthermore, methyl bromide is a toxic material. According to the U.S. EPA (2010), “exposure to high concentrations of it can result in central nervous system and respiratory system failure, as well as specific and severe deleterious actions on the lungs, eyes, and skin. Exposure to high concentrations has resulted in a number of human deaths”.

[2] The IPPC is an international treaty to secure action to prevent the spread and introduction of pests of plants and plant products, and to promote appropriate measures for their control. It is governed by the Commission on Phytosanitary Measures (CPM) which adopts International Standards for Phytosanitary Measures (ISPMs) (IPPC, 2009).

On the other hand, some plastic pallets are treated with flame retardants, especially deca-bromine, which is a chemical fire retardant commonly added to the petroleum-based polymer pallets in order to raise ignition temperature, reduce rate of burning, and reduce time to smoke generation to be equivalent or better than standard wooden pallets (NWPCA, 2009). There have been warnings about the dangers of using pallets treated with deca-bromine in the hydrocooling process for fruits and vegetables as well as raised concerns about the potential carcinogenic effect of deca-bromine (Brindley, 2009).

1.2 SUSTAINABLE DEVELOPMENT

Sustainable development is one of the most fundamental challenges confronting humanity. While everybody agrees about the need for sustainable development, the term still suffers from difficulties because there is no commonly accepted definition.

The notion of progress as something that is possible endlessly into the future was first challenged in 1972 in a report called *The Limits to Growth*, published by the Club of Rome, an international association of scientists, business executives, public officials, and scholars. The report challenged the idea of progress that compares the present with the past, and considers the future an endless possibility for further growth and improvement; on the argument that it failed to acknowledge the obvious truth that resources are finite, and hence growth dependent on resources cannot be endless (Meadows et al., 1972).

The World Conservation Strategy[3] was aimed at policy-makers, development practitioners, and conservationists. It defined *conservation* in human terms as "the management of human use of the

[3] The World Conservation Strategy is a document published in 1980 and prepared by the International Union for Conservation of Nature and Natural Resources (IUCN) (currently the World Conservation Union) with the cooperation of the World Wildlife Fund (WWF) and the United Nations Environment Programme (UNEP), which explains the contribution of living

biosphere so that it may yield the greatest sustainable benefit to present generations while maintaining its potential to meet the needs and aspirations of future generations". *Development* was defined as "the modification of the biosphere and the application of human, financial, living and, non-living resources to satisfy human needs and improve the quality of human life. For development to be sustainable it must take account of the social and ecological factors as well as the economic ones" (IUCN-UNEP-WWF, 1980). These definitions got close to the concept of sustainable development.

However it was the World Commission on Environment and Development that brought the idea of sustainable development into broader discussion; although it was not until the United Nations (UN) Conference for Environment and Development (or also known as Earth Summit) in Rio de Janeiro in 1992 that the concept was discussed in a global public policy debate. *Our Common Future*, the book of the UN World Commission on Environment and Development, also known as the *Brundtland Report*, defined sustainable development as the *"development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs"*. This concept implies that there are limits on environmental resources and the ability of the biosphere to absorb human activities. These limits are seen to have roots in technological inadequacies and inequitable social organization. Thus, sustainable development must entail a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are made consistent with future as well as present needs (World Commission on Environment and Development, 1987).

The overall driver used to begin the discussion of technological change, though phrased mathematically, is largely a conceptual expression of what factors create environmental impact in the first place. This equation represents environmental impact (I), as the product of three variables, *(i)* population (P), *(ii)* affluence (A), and *(iii)* technology (T), known as the Master Equation or *IPAT Equation*. This equation,

resource conservation to human survival and to sustainable development, identifying the priority conservation issues and the main requirements for dealing with them and proposing ways for effectively achieving the Strategy's aim (WCS).

along with the modern environmental movement, was born around 1970. Although the IPAT equation was once used to determine which single variable was the most damaging to the environment. an industrial ecology view reversed this usage, recognizing that increases in population and affluence can, in many cases, be balanced by improvements to the environment offered by technological systems (Chertow, 2001).

Corporations and organizations have started to measure their success through traditional economic factors and social and environmental values. In this evolution, some have categorized sustainability into three primary components often referred to as *the triple bottom line*: economic, social and environmental components (also known by *people, planet, and profit*). Triple bottom line attempts to describe the social and environmental impact of an organization's activities, in a measurable way, to its economic performance in order to show improvement or to make evaluation more in depth (Dictionary of Sustainable Management, 2009).

Walmart announced in 2005 three environmental goals: to be supplied 100 percent by renewable energy, to create zero waste, and to sell products that sustain resources and the environment. Walmart has been continuously focused on efforts to improve the efficiency and lower the greenhouse gas (GHG) emissions of their stores (Walmart, 2010).

Johnson & Johnson increased its use of rail to transport freight within the U.S. and between the U.S. and Canada by approximately 24 percent in 2009, equivalent to removing more than 6,800 trucks from the highways. This reduced congestion, decreased the risk of driver-related accidents and saved more than 630,000 gallons of diesel fuel, eliminating approximately 6,800 tons of CO_2 emissions - a 28 percent reduction in emissions for these shipments since 2008. Further, their investments in renewable energy reduced CO_2 emissions from their worldwide facilities by 15.9 percent in 2009 compared to 1990 (J&J, 2010).

In addition, Procter & Gamble uses a life cycle assessment approach to focus their sustainable innovations on areas where they will have the most meaningful environmental improvement. For example, innovative designs avoided the use of 312,000 metric tons of packaging material since 2007, allowing saving 735 metric tons of paper per year, 368 fewer truck trips, and 80 percent reduction in ink usage. Their efforts in operations have allowed a percentage reduction per unit production of 50 percent in energy usage, 53 percent in CO_2 emissions, 55 percent in waste disposal, and 55 percent of water usage since July 2002. P&G is focused on improving the logistics stage of the supply chain by implementing changes to the rate, route, mode, and method of transportation. Their long term operational end-points are to power their plants with 100 percent renewable energy, emitting no CO_2 or toxic emissions, using 100 percent renewable or recycled materials for all products and packaging, and having cero consumer and manufacturing waste go to landfills (P&G, 2010).

Similarly, a growing number of firms have begun to develop the next generation of clean technologies to drive future economic growth. BP and Shell are ramping up investments in solar, wind, and other renewable technologies that might ultimately replace their core petroleum business. In the automotive sector, Toyota and Honda, have already entered the market with hybrid power systems in their vehicles, which dramatically increase fuel efficiency. Firms such as Cargill and Dow are exploring the development of biologically based polymers to enable renewable feedstock, such as corn, to replace petrochemical inputs in the manufacturing of plastic (Hart, 2007).

All companies' efforts on taking social responsibility will help reduce resource consumption, waste, water use, and toxic emissions, which will allow conserving the environment, while increasing their economic performance.

Furthermore, sustainability is increasingly discussed by policy makers, the popular press, and journals in various technical fields. First considerations of sustainability can be traced back to decades of years ago,

although research literature shows that an increased interest on the term and the environment has been found since the 1990s and has quickly increased since then (Linton, Klassen, & Jayaraman, 2007).

Sustainability has become a wide ranging concept that can be applied to a large range of fields. Achieving a global commitment to live within sustainable limits will require a major collective effort. The development of new technologies and individual consciousness will be important factors to accomplish sustainable development.

1.3 Life-Cycle Assessment

The idea of a *life-cycle* has its roots in the biological sciences. Living organisms are born; they develop, mature, grow old, and ultimately, die. The way the organism develops and behaves along its life stages depend on its interaction with the environment. A similar path is followed by manufactured products. Natural resources are processed to give materials. These are manufactured into products that are distributed and used. Products have a useful life, at the end of which they are discarded. Energy and materials are consumed at each stage, releasing greenhouse gases (GHG), and depleting natural resources. Product life-cycle stages (or phases) are: material extraction, manufacture, use, transportation, and disposal.

The study of resource consumption, emissions, and their impacts is called *life-cycle assessment (LCA)* (Ashby, 2009). In other words, LCA is a technique used to evaluate the environmental aspects and potential environmental impacts throughout a product's life-cycle from raw material acquisition through production, use, end-of-life treatment and disposal (SETAC, 1991). LCA is applied by: compiling an inventory of relevant energy and material inputs and environmental releases, evaluating the potential environmental impacts associated with identified inputs and releases, and interpreting the results to evaluate and implement opportunities to affect environmental improvements (EPAa, 2011).

Graedel and Allenby (2003) define LCA as "an objective process to evaluate the environmental burdens associated with a product, process, or activity… and to evaluate and implement opportunities to effect environmental improvements". It implies that everyone in the whole chain of a product's life cycle, from cradle to grave, has a responsibility and a role to play, taking into account all the relevant impacts on the economy, the environment, and the society. In addition, it allows a more sustainable direction by applying cleaner process and product options.

The Society for Environmental Toxicology and Chemistry (SETAC, 1991) published "A Technical Framework for Life-cycle Assessments", the first attempt at an international LCA standard. It explicitly outlined the components of contemporary LCA: goal definition, inventory assessment, impact assessment, and improvement analysis. In the late 1990s, the International Organization for Standardization (http://www.iso.org) released the ISO 14040 series on LCA as an adjunct to the ISO 14000 Environmental Management Standards.

The technique of LCA is still evolving. Energy has been commonly used to evaluate the impact of materials, processes, and activities. Energy has the merit that can be measured with relatively precision, and with appropriate precautions, and can be used as a proxy to measure the CO_2 footprint[4] (Ashby, 2009).

The definition of *end-of-life* refers to the point in time when the product no longer satisfies the initial purchaser or first user (Rose, Ishii, & Stevels, 2002). A product is at its end-of-life when it is at the end of its economic or physical life. It is either returned to the original manufacturer because of legal product take-back obligations or returned to another company for value-added recovery (Brito & Dekker, 2002). End-of-life scenarios (Kumar & Putnam, 2008) include reuse, remanufacture, recycle, incineration (combustion for heat recovery), and disposal to a landfill; reuse being the most preferred method of source reduction (EPAb, 2011).

[4] The CO_2 footprint is the associated release of CO_2 into the atmosphere, in kg of CO_2/kg, of the sum of all contributions per unit mass of materials extraction, manufacture, transport, use, and disposal (Ashby, 2009).

For pallets, the following end-of-life scenarios are possible (C. Merta, personal communication, July 15, 2009):

- Reuse: refers to using core pallets without making any changes (applicable to all type of pallets).
- Remanufacture (repair in pallet context): bringing damaged parts back to a functional condition, or replacing severely damaged parts with new ones (applicable only to wooden pallets).
- Recycling: taking component materials and processing them into the same material, or other useful material (known as downcycle) (applicable to plastic and metal pallets). Recycling of wood from pallets is always a downcycling step. It refers to grounding, and chipping pallets to produce landscape mulch or animal bedding; and furnishing for fiber-based products.
- Incineration: refers to destroying the pallet components by burning them for heat recovery or energy fuel (only applicable to wooden pallets).
- Disposal to a landfill: refers to disposing pallets by burying and covering them (applicable to all type of pallets).

While downcycling wooden pallets allows waste reduction and good use of materials, it requires the investment of additional energy to mulch the wood and transport it to the place where it will be used, which adds to the energy embodied in a wooden pallet. When plastic pallets get damaged, their material is recycled to be reused to make new pallets or used for other applications. Greenhouse gas (GHG) emissions are therefore offset by the avoided fossil fuel use for raw material acquisition.

Pallet combustion and landfilling uses energy for transporting and managing the waste, and produces GHGs to varying degrees. However, landfilling pallet material offers an opportunity to recover energy since the anaerobic decomposition of wood generates methane gas that can be captured by modern landfill systems. Because HDPE does not decompose in landfills there is no opportunity to recover energy from HDPE pallets that are landfilled. In addition, some of the energy released during combustion can be harnessed and used to power other processes, which results in offset GHG emissions from

avoided fossil fuel use. On the other hand, combusting pallets that have been treated with methyl bromide will liberate toxic and irritating chemicals (Cheremisinoff, 1999).

One of the main issues with shipping products on a pallet is recovering the pallet after delivery. It is very costly, and when shipping significant distances the cost of recovery is more than that of the pallet. This results in the abandonment of pallets, or in the case of single-use pallets, the disposal of the pallet. Most developed countries have created various types of pallet rental and management systems to prevent such outcomes.

In general, the end-of-life alternatives such as reuse, remanufacture, and recycling may lead to more sustainable solutions. Otherwise, incineration, when not for heat recovery, releases toxics to the environment. In addition, disposal to landfills refers losing materials that probably are still useful, while it contributes to emissions and toxics released into the earth.

1.4 Pallet Management

Pallets are commonly used to ship products from consumer product manufacturers to product distributors and/or retailers. Pallets are produced in many sizes depending on the product manufacturers' needs or specifications. Because they take up storage space, empty pallets must be returned or disposed of. This may seem like an insignificant problem for large retailers but one needs to remember that every product on the shelf in a retail store was most likely transported on a pallet. Pallet costs can run into millions of dollars for product distributors (Dana, 2010).

An option is to outsource pallet management to a logistical service company. By placing pallet management responsibilities in the hands of pallet experts, time, labor, and waste could be avoided.

The acceptance of third-party management systems in the U.S. pallet industry started at the end of the 1990s. These organizations manage their clients' pallet needs, lowering their handling problems related to sorting, cleaning, repairing, and disposal. Third-party pallet management, also known as pallet pooling, has increased in the past decade due to increases in material cost, environmental concerns, and the globalization of markets.

Pallet pooling can involve two types of reusable pallet logistics: leased pools and buy/sell programs. Companies can *lease* pallets to users who use them in a closed-loop environment, which facilitates recovery. After use, pallets are transported to one of the third-party's depot centers for storage until they can be redeployed to another customer elsewhere in the country, or if they are damaged to get repaired. In a *buy/sell* program pallets are sold to customers, transported with product through the supply chain and then repurchased by a local pallet management facility prior to being repaired and reused, or recycled (Bejune et al., 2002a; IFCO, 2009).

Various companies offer the service of pallet pooling. *Commonwealth Handling Equipment Pooling (CHEP)* is the global leader in wood pallet pooling services serving many of the world's largest companies. CHEP manufactures, collects, and repairs approximately 320 million pallets and containers from service centers placed in 75 countries, helping manufacturers transport their products to distributors and retailers (http://www.chep.com). In the U.S. this company handles approximately 80 million GMA wood block pallets, representing approximately 40 percent of the wood pallet market. The other 60 percent is represented by almost three thousand smaller pallet manufacturers, repair, and recycling centers (C. Herndon, personal communication, July 31, 2009). CHEP handles pallet and container supply chain logistics for customers in the consumer goods, meat, home improvement, beverage, raw materials, petro-chemical, and automotive industries. Its pallets are known to be colored blue.

PECO Pallet manufactures and offers to the grocery manufacturers and distributors of North America wood stringer and block pallets. Their pallets are known to be colored red, and represent approximately 1 percent of the white wood pallet industry in the U.S. (http://www.pecopallet.com).

IFCO Systems is an international logistics service provider with more than 210 locations worldwide. It operates a pool of more than 96 million RPCs (Reusable Plastic Containers) globally, which are used primarily to transport fresh products from producers to leading grocery retailers (http://www.ifcosystems.com). In the U.S., IFCO Systems provides a national network of pallet management services, including sorting, repair, and reissue (none are manufactured by the company). IFCO Systems is the market leader in this industry segment (L. Cochran, personal communication, July 31, 2009).

Intelligent Global Pooling Systems (iGPS) is a plastic pallet manufacture and service pooling company that handles approximately 2 million pallets in the U.S. They are known to be black or gray, because of their material recycled content (http://www.igps.net). *Ongweoweh Corp* is a pallet management company which repairs, collects, and manages approximately 2 million wood, plastic, and metal pallets in the U.S. (http://www.ongweoweh.com). As these companies, many other third-party pallet providers help in the management of pallets in the country.

Pallet pooling providers have become interested in the environmental impacts associated with the management of their clients' pallets. Product manufactures are highly focused in implementing sustainable effective supply chains, which has incentivized pallet pooling companies implementing sustainable logistic systems to stay competitive in the market. The way pallets are managed along the entire supply chain can make a notable difference on the environmental impacts arising from pallet operation practices.

CHAPTER II

LITERATURE REVIEW

The following chapter discusses the literature reviewed for the present research. The areas of study include: pallet life cycle stages, life-cycle assessments, pallet management, and multi-objective optimization.

2.1 PALLET LIFE CYCLE STAGES

Pallets play an important role for transportation of goods. Solid wood pallets account for an estimated 90 to 95 percent of all pallets in the U.S. (NWPCA, 2000). Wooden pallets are responsible for 2 percent of all Municipal Solid Waste (MSW) and over 3 percent of all Construction and Demolition Waste (C&D) landfilled in the United States (Bush, Corr, & Araman, 2001; McKeever, 1999) regardless the fact that technologies and markets exist that allow pallets to be reused, recycled, or converted into other products (Buehlmann et al., 2009). Companies have given high importance to pallet end-of-life scenarios. In fact, the industrial recycling of pallets emerged in the 1960s. Bush, Reddy, and Araman (1996) show in their study that various factors have contributed to the growth of pallet recycling by the industry: an increased awareness of the environment, the economic benefits of repairing and reusing wooden pallets and decreasing products handling costs, and the significant increase of disposal costs.

Studies have been developed that analyze the different pallet end-of-life scenarios (Gasol et al., 2008; Corbiere-Nicollier et al., 2001; Bejune et al., 2002b; Buehlmann et al., 2009; Bush & Araman, 2008, 2009).

Gasol et al. (2008) assess the environmental impact of current management systems of wooden pallets. They compare the benefits and drawbacks of high and low reuse rates as waste prevention strategy to recycling. The study concludes that reuse, combined with recycling as final disposal, instead of incineration and landfill, will reduce the waste generated and the demand for natural resources.

Furthermore, an assessment of biofibres replacing glass fibres as reinforcement in plastic pallets was performed by Corbiere-Nicollier et al. (2001). Since polypropylene (PP) is hardly biodegradable, incineration is preferred over landfills at the end of pallets useful life-cycle. Although PP incineration produces toxic heavy metals emissions (such as cadmium), it contributes to energy production. Landfills were not studied in detail, although since they occupy large surface areas it was concluded that they would be unfavorable. Pallet recycling avoids emissions due to pallet disposal and reduces emissions during product manufacturing. Moreover, the Buehlmann et al. (2009) report gives background information that supported the decision of the state of North Carolina to enact legislation to ban pallet landfilling, beginning in 2009.

Araman et al. (1998) show that it can be environmental friendly to apply wood pallet recovery, repair, and recycling. Doing so will reduce forest resource demands and waste in landfills. The total demand of pallets for 1995 was 560 million pallets, from which 411 million were new and 149 million recovered/repaired; which means that 1 out of 4 wood pallets purchased in 1995 was a recovered/repaired pallet. Nevertheless 223.6 million pallets entered the Construction & Demolition (C&D) and the Municipal Solid Waste (MSW) landfills (Araman et al., 1998).

Wood pallet production has increased from 411 million units in 1995 to 441 million units in 2006. Pallet manufacturers used 63.6 percent (by volume) hardwood and 36.4 percent softwood material in 2006. From 1995 to 2006, it was estimated that the number of pallets recovered by the pallet industry increased from 171 million to 321 million. Recovered wood material utilized by the pallet industry increased as a percentage of the total among those years, suggesting that recovered wood materials are

primarily satisfying any new demand for wood materials created by the pallet industry. Of all uses of recovered pallets, repaired pallets which get reused or sold increased from approximately 41 million pallets in 1992 to 370 million in 2006. It was estimated that 1.5 million recovered pallets were sent to landfills in 1992 and 1 million in 2006. In 1995 this represented 0.9 percent of the total recovered pallets compared to 0.25 percent in 2006. The number of pallets that were ground or chipped for landscape mulch production increased from 3.4 million in 1995 to 23 million in 2006 (Bejune et al., 2002b; Bush & Araman, 2008, 2009).

The environmental impacts of pallet end-of-life scenarios have been analyzed for wood and plastic pallets. Gasol et al. (2008) defined two reuse rates scenarios for industrial wooden pallets: high-reuse pallets and low-reuse pallets. The assessment shows that the high-reuse intensity pallets reduce the energy, wood consumption, and environmental impacts such as ozone depletion, acidification, and eutrophication, but not the global warming potential. The highest impact stages are transport, raw material extraction and manufacturing. Their study does not consider other raw materials such as plastics and/or metals.

The performance of plastic and wood pallets was studied comparing environmental considerations by Singh and Walker (1995). The study showed that the twin sheet thermo-formed HDPE plastic pallets had the best environmental performance followed by the structural foam HDPE pallets and the presswood pallets. Corbiere-Nicollier et al. (2001) illustrated a reduction in energy consumption and other environmental impacts with the substitution of glass fibre production by natural fibre production for plastic pallets. Their research states that transport pallets reinforced with China reed fibre prove to be ecologically advantageous if they have a minimal lifetime of 3 years compared with the 5-year lifetime of the conventional plastic pallet. Considering the entire life cycle, the polypropylene production process and the transport cause the highest environmental impacts among all life cycle stages.

The Timber Packaging and Pallet Confederation (TIMCON, 2008) claims that due to rising industry pressures and costs, timber remains the most sustainable material in the world for storage, transport, and movement of goods, as the production and processing of new timber pallets is highly energy-efficient, with a low carbon footprint.

Materials for pallets manufacturing play an important role in the end-of-life decision. Lacefield (2008) suggests that for years the pallet industry has argued which material has been the best choice. For many years companies analyzed their materials from a cost-effectiveness perspective. Today they are concerned with their sustainable performance.

2.2 LIFE-CYCLE ASSESSMENT

Life-cycle Assessment (LCA) has its roots in the 1960s, when scientists concerned about the rapid depletion of fossil fuels developed LCA as an approach to understand the impacts of energy consumption. Years later, global-modeling studies predicted the effects of the world's changing population on the demand for finite raw materials and energy resource supplies (Meadows et al., 1972). Various studies were conducted by the Midwest Research Institute (Hunt, 1974; Sheehan et al., 1998), and later by the consulting firm Franklin Associates Ltd. (Brindley, 2010; Hunt, Franklin, & Hunt, 1996; Hunt, Sellers, & Franklin, 1992; Saouter & Hoof, 2002), mostly for the private sector. A study for the Coca Cola Company had as an objective to determine which type of beverage container had the lowest carbon releases to the environment and the fewest demands for raw materials and energy (Franklin Associates, 1991).

In the 1970s, the U.S. Environmental Protection Agency (EPA) refined the LCA methodology, creating an approach known as Resource and Environmental Profile Analyses (REPA). Driven by the oil crisis of

1973, approximately 15 REPAs were performed between 1970 and 1975. Through this period a protocol for conducting these studies was developed (Hunt et al., 1992).

In the late 1970s and early 1980s, environmental concerns shifted to issues of hazardous waste management. As a result, life-cycle logic was incorporated into the emerging method of risk management, which was used to develop environmental protection standards (Stilwell et al., 1991). In 1990, a life-cycle assessment was completed comparing disposable diapers to washable cloth diapers. Disposable diapers show to consume less energy and water than reusable diapers; however, create more post-consumer waste (World Resources Institute, 1994). A similar study was conducted for the Council for Solid Waste Solutions, which compared the energy and environmental impacts of paper to that of plastic grocery bags. The study concludes that plastic bags are better in terms of environmental impacts compared to paper bags (Council for Solid Waste Solutions, 1990).

Today approximately 90 percent of pallets are made of timber (http://www.epal-pallets.org). However, plastic pallets are expected to become a serious competitor to wooden pallets. The Netherlands Packaging and Pallet Industry Association conducted a study for Commonwealth Handling Equipment Pooling (CHEP), the global leader in pallet and container pooling services. The life-cycle assessment (LCA) tool was used to compare the environmental impacts of wood pallets and plastic pallets (50 percent recycled plastic and 50 percent new HDPE), when used multiple times. The results of the analysis show that, because the impacts of manufacture and use phases for plastic pallets are much higher, wood pallets are more environmental friendly than plastic pallets. They also conducted a LCA to evaluate single-use wood pallets versus multi-use wood pallets (per handling cycle), and concluded that multi-use wood pallets are preferred for the environment over single-use wood pallets (CHEP, 2008; Hamner & White, 2007).

Conversely, an independent LCA was conducted by iGPS (Intelligent Global Pooling Systems), a plastic pallet pooler, to examine the environmental impacts of three types of pallets commonly used: the

pooled multi-use wood pallet, the single-use wood pallet and iGPS's pooled all-plastic pallet. The analysis found that iGPS's all-plastic pallet had significantly less environmental impact than both the pooled multiple-use wood pallet and single-use wood pallet (iGPS, 2008).

CHEP's LCA conducted in 2007 did not cover pooled plastic pallets because they were not widely available. CHEP's 2009 LCA results released in March 2010 showed some improvements of whitewood pallets compared to both pooled wood and plastic, although the results pointed to pooled wood (especially CHEP pallets) as the most environmentally preferable and sustainable option. The assessment was conducted by Franklin Associates, a leading consultant group specializing in life-cycle inventory analysis and solid waste management. According to CHEP's 2009 study, a CHEP pallet generates 48 percent less solid waste, consumes 23 percent less total energy, and generates 14 percent less GHG than a pooled plastic pallet. Compared with limited use white wood pallets, CHEP pallets generates 50 percent less solid waste, consumes 19 percent less total energy, and generates 5 percent less GHG (Brindley, 2010).

Dr. Mark White, former director of the Center for Unit Load Design at Virginia Tech, envisions the idea of the convergence of all aspects of the supply chain to reduce waste, cut costs, improve efficiencies, and benefit the environment. He states that LCA is a measuring tool that does not objectively compare raw material renewability. This is a reason why in some studies wood pallets appear to be the most environmental friendly, while other sources state that plastic pallets are. Dr. White is quoted in Brindley (2007) as "it will depend very often on how the pallet is being used as to whether the impact is greater. Other issues like how often the pallet is reused become a factor".

2.3 MULTI-OBJECTIVE OPTIMIZATION

A linear programming problem may be defined as the problem of maximizing or minimizing a linear function subject to linear constraints. The constraints may be equalities or inequalities. Linear programming is used as a mathematical optimization technique for organizing or allocating resources (Ferguson, 1995). If the unknown variables are all required to be integers, then the problem is called an integer programming problem; however, if only some of the unknown variables are required to be integers, then the problem is called a mixed integer programming problem. Industries that use mathematical programming models include transportation, energy, distribution, telecommunications, and manufacturing. It has proved useful in modeling diverse types of problems in planning, routing, scheduling, assignment, and design.

The problem of systematically and simultaneously optimizing a collection of objective functions is called multi-objective optimization. These types of problems do not have a unique solution that simultaneously minimizes, or maximizes, each objective. Quantifying how much better one solution is compared to many others, is the goal when setting up and solving a multi-objective optimization problem (Marler & Arora, 2004). The pareto frontier marks the reachable outcomes under a best response behavior. The value of the tradeoff rate informs the decision maker concerning the exchange between the objective values if one moves along the pareto frontier.

The *epsilon-constraint method* is one of the techniques used for solving multi-objective problems. It solves single objective problems obtained by transforming all but one of the objectives into a constraint (Bérubé, Gendreau, & Potvin, 2009). In general, with objectives $f_1, f_2, \ldots, f_m$, the *epsilon-Constraint method* repeatedly solves optimization problems of the form (assuming minimization of all objective functions):

$$
\begin{aligned}
&\textit{minimize } f_l(x) \\
&\qquad \textit{subject to } f_j(x) \le \epsilon_j \quad \forall j = 1,2,\ldots,m, j \ne l \\
&\qquad x \in S
\end{aligned}
$$

where $l \in \{1,2,\ldots,m\}$ and *S* is the feasible region.

Let $P_1(\varepsilon_2)$ represent the problem where the objective function f_1 is minimized subject to the minimum value when f_2 is minimized ensuring that $f_2(x)=\varepsilon_2$, and $z_1(\varepsilon_2)$ is the value of the optimal solution to this problem. Then, to generate a set of solutions, each with a potentially different tradeoff between both objective functions, the algorithm below is executed.

Algorithm Pareto

Require: Scaling factors $\propto_1, \ldots, \propto_n$

Let $z_1^* =$ minimize $f_1(x)$subject to $x \in S$

Let $z_2^* =$ minimize $f_2(x)$subject to $x \in S$

for $i = 1$ to n do

Set $\epsilon_2 = (1 + \alpha_i) * z_2^*$

Solve $P_1(\epsilon_2)$ for x^* and value $z_1(\epsilon_2)$

end for

Multi-objective optimization models have been used for a large field of applications, including engineering, finance, supply chain, product, and process design, among others. Sabri and Beamon (2000) developed an integrated multi-objective supply chain model that incorporates production, delivery, and demand uncertainty to design efficient, effective, and flexible supply chain systems. Further, Mahnam et al. (2009) developed a multi-objective inventory model including total cost and fill rate for an assembly supply chain network under different uncertainties. Uncertainty results from customer's demand variability or unreliability in external suppliers.

Moreover, research has considered both forward and reverse logistics operations, establishing a new multi-objective optimization model of logistics facility layout. The objectives of this optimization model were to minimize the total costs of the forward and reverse logistic process while maximizing customers' satisfaction degree (Wang et al., 2008). Likewise, multi-objective optimization has been used for transportation issues. Ma (2010) developed a model which not only optimizes traffic signal timing but also lane allocation at signalized intersections networks.

Sustainability considerations are starting to be addressed in enterprise supply chains, from the raw material stage to product distribution stage. Sustainability, involving the multiple objectives of social, economic, resources, and environmental sustainability, can be sometimes conflicting. Zhou et al. (2000) propose a multi-objective optimization model to evaluate the objectives of social, economic, resources and environmental sustainability. The application of this approach was illustrated through a case study on sustainable supply chain optimization and scheduling of a petrochemical complex. The results obtained show that this approach is a useful tool for decision-making. Moreover, Wang et al. (2010) studied a supply chain network design problem with environmental concerns. Their research focused on the design phase, and proposed a multi-objective optimization model that captures the trade-off between the total cost and the environment influence in the handling and transportation process, allowing an effective tool in the strategic planning for green supply chain. Further, research has been done on extending the traditional process design framework to green process design and industrial ecology leading to sustainability (Diwekar & Shastri, 2010). Likewise, environmental and economic objective functions were used simultaneously to select the operating conditions of a steam and power plant. The methodology developed by Martínez and Eliceche (2009) is used to estimate the potential environmental impacts during the most important life cycle stages associated with imported fuel and electricity in the utility plant.

2.4 Problem Statement

As overall summary, the review of the literature shows that environmental management has gained increasing interest in the field of supply chain management. However, there is a need for effective and efficient optimization techniques that address pallet operations within an entire supply chain and consider pallets environmental impacts and costs. This literature review shows a gap of researches that study pallet life cycle stages and the different pallet management systems.

Furthermore, a full picture of the environmental consequences associated with pallet choice will need to include the tradeoffs between using more energy intensive plastic pallets over longer periods of time versus using more, less energy intensive wood pallets for shorter periods of time.

Pallets are indirectly responsible for a share of the emissions that are generated as the pallets and their cargo move through the supply chain. Primary freight transportation methods (ship, rail, air, and truck) are all fossil fuel based, and heavier pallets will require more fuel to transport them than lighter pallets. The combustion of the additional fuel will result in greater emissions of CO_2, SO_x, NO_x, and various forms of particulate matter. Tradeoffs can arise where lighter but less durable pallets could be preferred to heavier ones because they are responsible for fewer emissions as they move through a supply chain. Methods are needed to help logistics system designers understand and evaluate these potential tradeoffs.

Beyond the tradeoff between cost and durability, there are other issues that can drive the choice of pallet and the selection of a pallet management strategy. As organizations work to develop more sustainable supply chains, they will need to take into account environmentally oriented criteria such as: the embodied energy of the materials in the pallet; the energy of the pallet manufacturing process; the differential emissions that arise during transportation due to the weight differences between pallets of dissimilar materials; and impacts associated with the various end-of-life alternatives available for different types of pallets (mulching, incineration, landfilling, etc).

Finally, this study aims to address such a gap by providing a model that studies pallet life cycle stages and their operations to determine the mix of pallets (type, quantity, and pallet management system) for product distribution that balances overall environmental impacts and costs according to companies' needs. The proposed model and approach will provide companies seeking to engage in more sustainable practices in their supply chains and distribution with insights and a decision making tool not previously available.

CHAPTER III

METHODOLOGY

Linear mathematical programming is used to design the system that will determine the optimal mix of pallets (quantity, material, and pallet management system) to be delivered among facilities, in order to reduce the use of resources, transportation, thus fuel emissions. A multi-objective optimization model is used to measure the tradeoffs between the system environmental impacts and costs. The supply chain considers multiple pallet providers, consumer product manufacturers, distribution centers, retailers, and return centers.

<u>Outline of Chapter III - Methodology</u>

3.1) Pallet network, a proposed model. The flow of pallets between pallet providers, consumer product manufacturers, distribution centers, retailers/stores, and return centers is explained;

3.2) Detailed model based on pallet life-cycle stages, including pallet end-of-life alternatives;

3.3) Modeling approach: *(i)* model assumptions and research limitations; *(ii)* abbreviations; *(iii)* pallet lifespan; *(iv)* pallet costs; *(v)* nomenclature; *(vi)* objective functions coefficient descriptions; *(vii)* decision variables; *(viii)* model logic; and *(ix)* time representation;

3.4) Mathematical programming model, including objective functions and constraints;

3.5) Input data collection.

3.1 PALLET NETWORK - A PROPOSED MODEL

The flow of consumer products, especially in the grocery industry, is illustrated in Figure 2. Consumer product manufacturers require pallets to transport their products to distribution centers. Pallets are then unloaded and restacked at the distribution centers with specific orders for the retailers/stores. Loaded pallets are then sent to these retailers, unloaded upon arrival, while unloaded pallets are sent back to pallet providers. From retailers pallets are sent to return centers where they are then sorted by type (or by provider) and sent to the different pallet owners. However, other pallets, such as whitewood pallets for example, may be discarded (disposed) directly after used, in which case the return center may be located at the retailer. Pallets may flow from return centers back to distribution centers or even to consumer product manufacturers for reuse, depending on the pallet management approach of each pallet type. In addition, pallet providers may decide on the pallet retirement alternative.

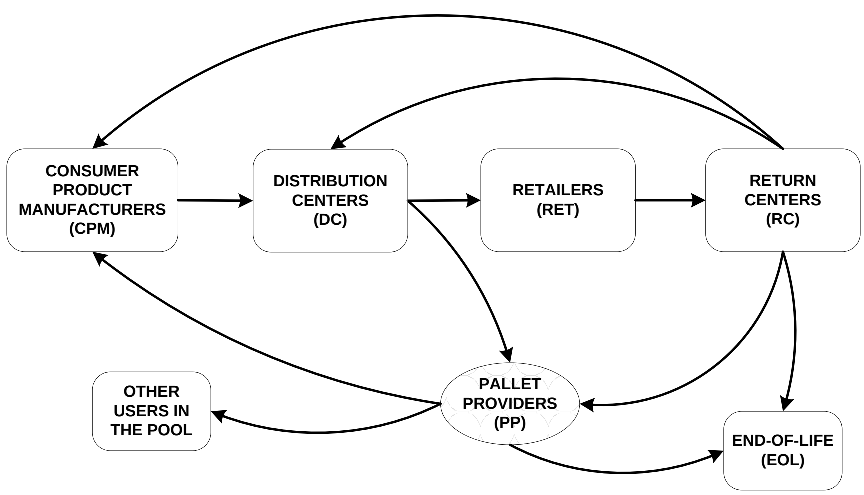


Figure 2. An example of a network of physical flow of pallets

When pallet providers work under a buy/sell program, they sell their manufactured pallets to users (in this case consumer product manufacturers). Pallet ownership is transferred with the pallet, from the pallet manufacturer to the consumer product manufacturer, and further down the chain to the product distributor and retailer. The product distributor and/or retailer then sell the pallets after they have been used to the pallet provider. Thus, two pallet costs are involved under this program: the pallet purchase cost (between the pallet provider and the consumer product manufacturer); and the selling cost (between the product distributor and/or retailer and a pallet provider).

Pooled pallets are always owned by the pallet pooling company. These companies lease their pallets to the consumer product manufacturers. A company may contract a service level that provides a fixed number of pallets (e.g. 40,000), or in other cases a variable number of pallets based on their monthly needs. The leasing cost usually involves a leasing cost (also known as issue cost), a cost per pallet per day, and a cost of return when each pallet gets transferred. This cost may differ from one consumer product manufacturer to another, and can depend on quantity, facility locations, and other variables. Some pallet providers may charge the product distributors or retailers for returning their pallets to their depot centers; while other pallet providers may give a credit to the company who returns the pallets.

Eventually a pallet constructed from any material will come to the end of its useful life. The methods by which pallets are disposed of when they must be retired include reuse, repair, recycle, downcycle, landfill, and incineration.

A detailed network may include multiple pallet providers (PP_1, PP_2… PP_n), multiple consumer products manufacturers (CPM_1, CPM_2… CPM_n), distribution centers (DC_1, DC_2… DC_n), retailers (RET_1, RET_2… RET_n) and return centers (RC_1, RC_2… RC_n) (Figure 3).

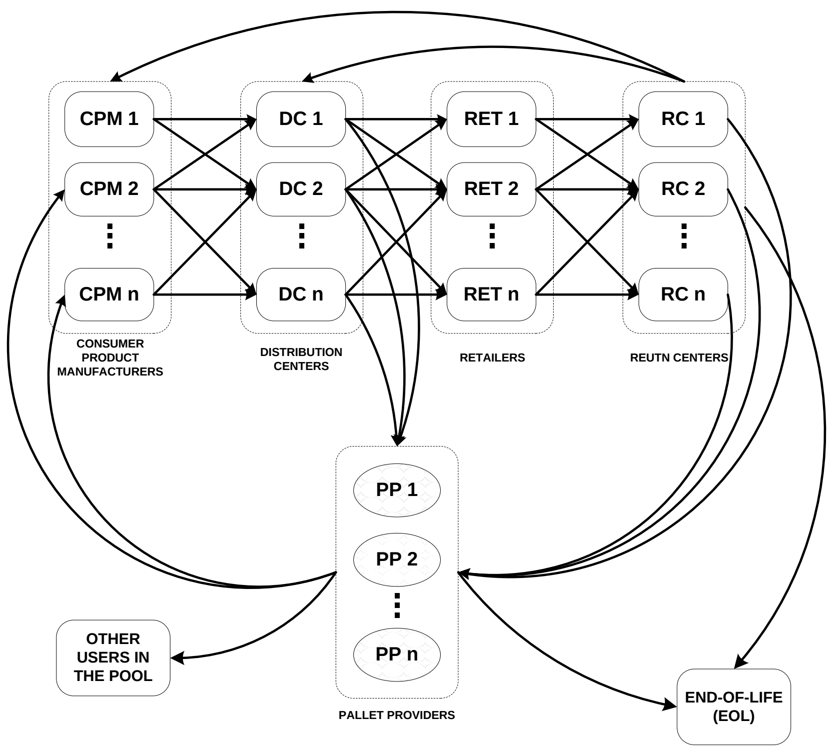


Figure 3. Pallet supply chain network applied to multiple facilities

3.2 Detailed Model

In order to integrate environmental impacts arising from pallet operations, the system modeled was designed based on pallets life-cycle stages. Figure 4 incorporates the beginning and end-of-life stages for a pallet to the diagram presented in Figure 2. The pallet stages considered are: raw material acquisition, manufacture, use phase (composed by consumer product manufacturers, distribution centers, retailers, and return centers), as well as various end-of-life (disposal) scenarios. As a result, pallet providers are not being physically represented, but their actions (reuse, remanufacture, etc.) are included.

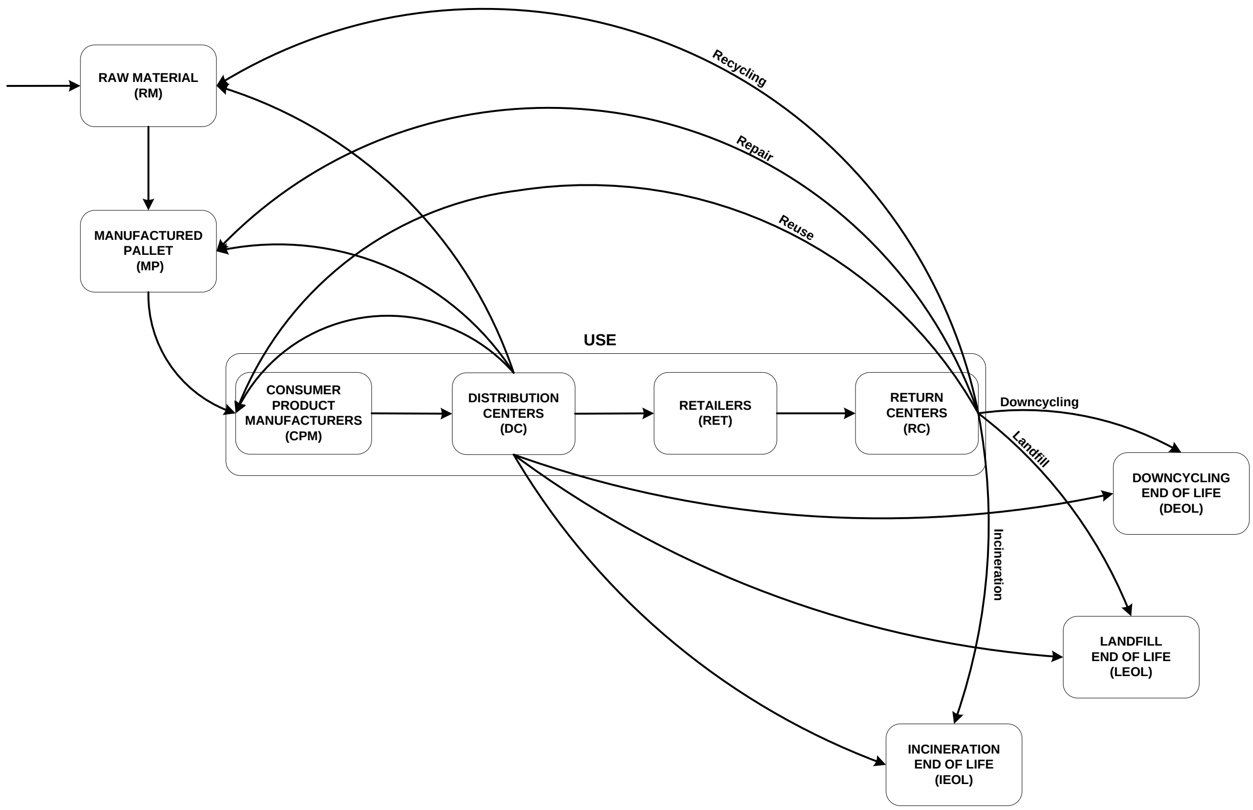


Figure 4. Life-cycle network of pallets

For instance, for a hardwood pallet, the arc into "Raw Material" models the extraction of wood used to manufacture new hardwood pallets. The CO_2 emissions consequent on the extraction of unit mass of material (in this case wood) include those emissions associated with transport, the generation of the electric power used by the plant to cut the lumber, and that of feedstock and hydrocarbon fuels if any. As a result, the CO_2 footprint of the raw material stage is then the sum of all the contributions per unit mass of usable material exiting the plant (Ashby, 2009). The arc from "Raw Material" to "Manufactured Pallet" models the actual fabrication of a pallet. For example, a plastic pallet may be manufactured with an injection-molding machine. Further, the CO_2 footprint from pallet manufacture does not only include

the CO_2 released during the manufacturing process, but other emissions created by the plant for the pallet to be made (including that of feedstock and hydrocarbon fuels, for example) (Ashby, 2009).

In general, the arc coming into "Raw Material" models the extraction of those materials, such as wood and plastic, used to manufacture new pallets. The arc from "Raw Material" to "Manufactured Pallet" represents the manufacture of pallets made of raw and/or recycled material. The arc from "Manufactured Pallet" to "Consumer Product Manufacturer" models the pallets supplied by pallet providers/manufacturers to consumer product manufacturers, and can include new fabricated pallets and/or repaired wooden pallets. The use phase starts when the "Consumer Product Manufacturer" ships their products on pallets to the "Distribution Centers" and further to "Retailers". Empty pallets are sent to "Return Centers". From this return (or collecting) center, pallets are sold and/or sent back to the pallet providers, who then will decide on the pallet end-of-life scenario. Pallets can also be returned from the distribution centers to the pallet providers.

Pallet disposal scenarios include reuse, recycle, repair, downcyle, landfill, and incineration. As a result, the system models pallets flowing from product distributor's facilities (specifically from the distribution centers and return centers) to each of pallet end-of-life alternatives representing the impact of the selected disposal scenario. Accordinlgy, arcs from either "Distribution Centers" or "Return Centers" into "Consumer Product Manufacturer" models the scenario *reuse*. In a similar way, *recycle* (material recycling, such as plastic and metal) is modeled by pallets flowing into "Raw Material". *Repair* is modeled by pallets flowing into "Manufactured Pallet". *Downcycling* is represented by pallets flowing into "Donwcycling End-of-Life" which refers to chipping and grounding the wood into by products such as animal bedding and landscape mulch. The impact of sending a pallet to *landfill* is illustrated by pallets flowing into "Landfill End-of-Life". *Incineration* is modeled by pallets flowing into "Incineration End-of-Life".

3.3 MODELING APPROACH

Different tools were considered and evaluated to give application to the model proposed. The literature shows research for supply chain applications modeled with fuzzy logic (Qin & Ji, 2009; Zhang et al., 2007), neural networks (Wang et al., 2008), systems dynamics (Georgiadis & Besiou, 2008; Kamath & Roy, 2007), simulation (Iannoni & Morabito, 2006; Kara, Rugrungruang, & Kaebernick, 2007), and operations research (Mahnam et al., 2009; Martínez & Eliceche, 2009; Sabri & Beamon, 2000; Wang et al., 2008; Zhou et al., 2000). Further, logistics systems were found to be modeled by using linear programming (Neto et al., 2009; Sheu, Chou, & Hu, 2005) and mixed-integer programming (Xanthopoulos & Iakovou, 2007). From the methods reviewed, mixed-integer programming was chosen because these models can be solved quickly. Thus, one can manipulate the parameters of the model and analyze the sensitivity of solutions to those parameters.

There are multiple choices and attributes for pallet material (hardwood, softwood, metal, cardboard, or plastic), management (buy/sell, lease), material toxicity (such a potential carcinogenic effect of deca-bromine and possible nervous system failure caused by methyl bromide), and end-of-life disposition (reuse, repair, recycle, downcycle, incineration or landfill), each of which can affect the cost and environmental impact of possessing and using a pallet. If a decision maker is concerned with only cost objectives, and wishes to maintain a constant inventory of pallets in the supply chain, then he/she can use traditional economic analysis methods to make these choices. Challenges may arise when the purpose is to decide on pallet management systems and material when both objectives (cost and environmental impact) are considered. Tradeoffs between the system environmental burden and its costs will likely arise.

One approach is to develop a methodology for converting environmental impacts (such as CO_2 emissions) to dollars, and then focus on a single objective, total cost, that includes the dollar cost of those environmental impacts. An advantage of this approach is that once the methodology for costing

environmental impacts is developed, well-known economic analysis methods can be used for making decisions. A disadvantage is that developing such methodology adds a layer of complexity to the decision-making process and will likely require assumptions that the final decisions prescribed by the analysis may be sensitive to. For example, there are no accurate tools known today that can precisely measure the monetary value of eco-system depletion and impacts on biodiversity.

Another option is to deal with the two objectives directly and in their own units of measure. This is the approach selected in this research, and, to do so, these potential pallet choices have been chosen to be modeled with a mixed-integer program (as a minimum cost multi-commodity network flow problem). For effects of the study the combination of material and management program is referred as a *pallet type*.

3.3.1 MODEL ASSUMPTIONS AND RESEARCH LIMITATIONS

It is assumed that by choosing a pallet provider, the decision maker likely also chooses the end-of-life disposition of pallets returned to that provider. Also, for pallets that are owned by the decision maker's organization, policies regarding the end-of-life disposition of pallets are likely already in place and cannot be changed on a pallet-by-pallet basis. Thus, the model is limited to choosing the material each pallet is made of and how it is managed, while still considering the environmental impacts of the end-of-life disposition dictated by that management program.

In addition, it is assumed that pallets are being used consistently, meaning that pallets may not stay idle for long time; thus pallets flow continuously through the nodes while time periods pass.

The need for pallets is modeled by assuming it is known with certainty the demand for products at the distribution centers and retailers. In addition, a pre-inventory of pallets exists only at the distribution centers, used to fulfill retailers' demand during the first time period.

This research focuses on GMA standard pallets (48x40). Oak-hardwood is used as base for wood pallet production, and low alloy steel for nails fabrication; high-density polyethylene (HDPE) is used for plastic pallets manufacture, which internally have low carbon steel reinforcement bars. This research focuses only on wooden and plastic pallets; metal pallets are not included. Pallets management systems modeled include buy/sell programs and leased pools.

Although this study frames the environmental impacts of pallet manufacturing, use, and disposal with respect to all aspects of sustainability, the focus of the model is on carbon footprint (in particular CO_2) of the operations. Impacts to human health, biodiversity, eco-system depletion, etc. are not addressed in this study.

Other modeling assumptions include: all wood is used for pallet fabrication and all recycled plastic is used in production of new plastic pallets. There are an unlimited number of new pallets that can be manufactured. The same carbon dioxide footprint applies when manufacturing pallets made of raw or recycled plastic. When pallets get repaired or recycled, supply of new pallets for replacement is readily available. The possibility of CO_2 emissions offsets for energy production when pallets get incinerated is not being modeled. Truck service is readily available and is the only transportation mode used. Only one specific pallet management system can be used by each consumer product manufacturer. The residence time of a pallet leased is 30 days.

3.3.2 ABBREVIATIONS

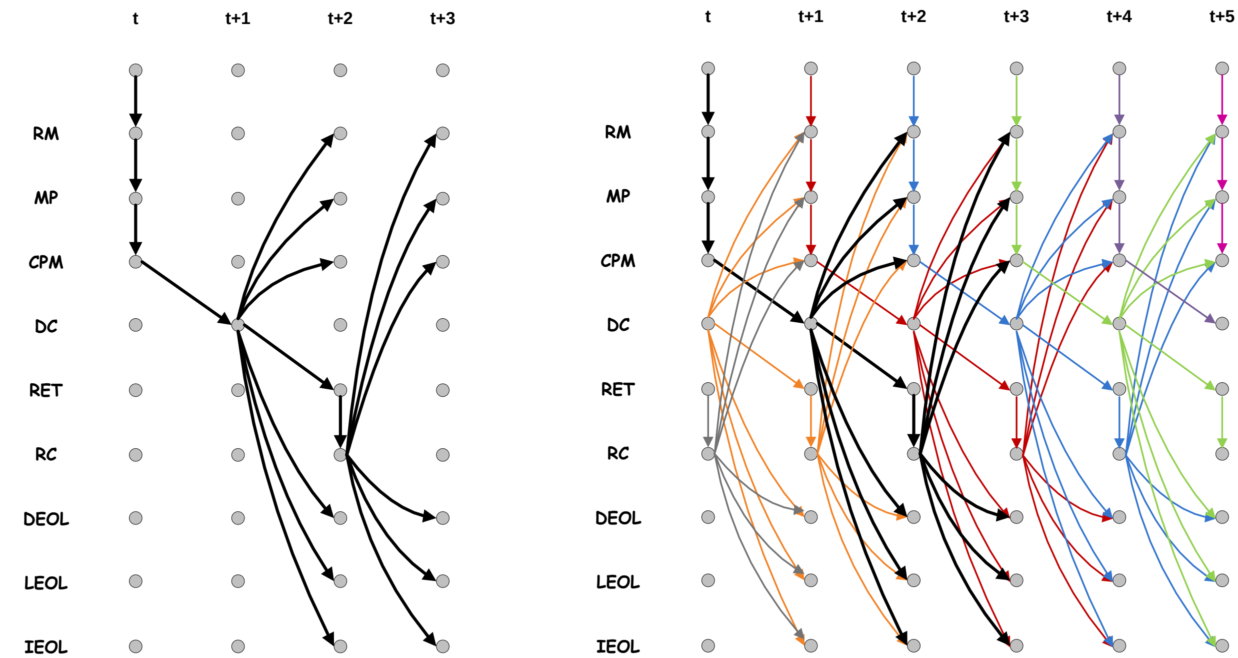
The following abbreviations are used to identify each node set *N* in Figure 4:

Table 2. Abbreviations used to identify each node set *N*

Abbreviation	Node
RM	Raw Materials
MP	Manufactured Pallets
CPM	Consumer Product Manufacturers
DC	Distribution Centers
RET	Retailers
RC	Return Centers
DEOL	Downcycling End-of-Life
LEOL	Landfill End-of-Life
IEOL	Incineration End-of-Life

3.3.3 MODEL TIME REPRESENTATION

Pallets flow within two different time periods in arcs *(CPM,DC)*, *(DC,RET)*, *(RET,RC)*, *(DC,EOL)*, and *(RC,EOL)*. This way the model considers that products can take a few days, depending on the distance, since they leave the consumer product manufacturers' facilities until they arrive at the distribution centers (or warehouses); further, pallets may be stored at the distribution centers for some time period before they are shipped to the retailers. Similarly, different time period are considered in arcs *(DC,EOL)* and *(RC,EOL)* since empty (unloaded) pallets are sent first to pallet providers before they are sent to the different locations depending on their end-of-life scenario (if they are being either reused, repaired, recycled, downcyled, incinerated or sent to landfill). A graphical representation of time is shown in Figure 5.



(a) Flow of pallets manufactured in period *t* **(b) Flow of pallets manufactured in each time period**

Figure 5. Time representation for nodes in set *N*

Figure 5(a) illustrates the flow of pallets per cycle for those manufactured at time period *t*. In addition, Figure 5(b) is a representation of the network with all possible flow of pallets being manufactured in each time period *t* (including *t+1*, *t+2*, etc.). For example, the darker black lines in the Figure 5 models pallet life cycle stages as follows:

i) the extraction of raw material and pallet manufacture *((RM,t),(MP,t));*

ii) pallet shipment from pallet manufacturer to consumer product manufacturer *((MP,t),(CPM,t));*

iii) pallet leaving the consumer product manufacturer in period *t* and arriving at a distribution center in period *t+1* *((CPM,t),(DC,t+1));*

iv) transportation of a loaded pallet leaving the distribution center in period *t+1* and arriving at the retailer in *t+2* *((DC,t+1),(RET,t+2));*

v) pallet sent to an end-of-life scenario from the return center:

a. *(RC,t+2),(CPM,t+3) representing reuse;*

b. *(RC,t+2),(MP,t+3) representing repair;*

c. *(RC,t+2),(RM,t+3) representing recycle;*

d. *(RC,t+2),(DEOL,t+3) representing downcycle;*

e. *(RC,t+2),(LEOL,t+3) representing landfill; or*

f. *(RC,t+2),(IEOL,t+3) representing incineration;*

vi) pallet sent to an end-of-life scenario from the distribution center if the pallet was damaged and did not make it to the retailer*: (a) (DC,t+2),(CPM,t+3) representing reuse; (b) (DC,t+2),(MP,t+3) representing repair; (c) (DC,t+2),(RM,t+3) representing recycle; (d) (DC,t+2),(DEOL,t+3) representing downcycle; (e) (DC,t+2),(LEOL,t+3) representing landfill; or (f) (DC,t+2),(IEOL,t+3) representing incineration).*

3.3.4 PALLET LIFESPAN

For the purpose of this work, the lifespan of a pallet is represented by including the pallet failure fraction per cycle. The system models damaged pallets leaving from the Distribution Centers (DC) and the Return Centers (RC). Since pallets are first used at the Consumer Product Manufacturer (CPM), it is assumed that the percentage of damaged pallets may be negligible to consider a failure fraction at this location. In addition, in some cases the return center may be at the retailer, which could be easily modeled if that is the case; for this reason a failure fraction is neither applied to pallets leaving the retailers.

For modeling purposes, one cycle is considered the entire pallet sequence starting at the pallet manufacturer or provider (PP), through the consumer product manufacturer (CPM), distribution center (DC), retailer (RET), return center (RC), and ending with the pallet provider (when pallets are being sold or returned). In addition, it is assumed that the same number of trips and handlings per trip apply from node PP to node DC, and from node DC to RC (Figure 6). Because all new/repaired/recycled pallets may originate at node PP the amount of damaged pallets leaving from the RC will be greater than pallets leaving from the DC. These damaged pallets are then sorted to the different end-of-life scenarios (repair, recycle, downcycle, landfill, and incineration). Note in the figure that all pallets leaving the DCs and RCs may be sent to the pallet providers first, before ending at an end-of-life scenario.

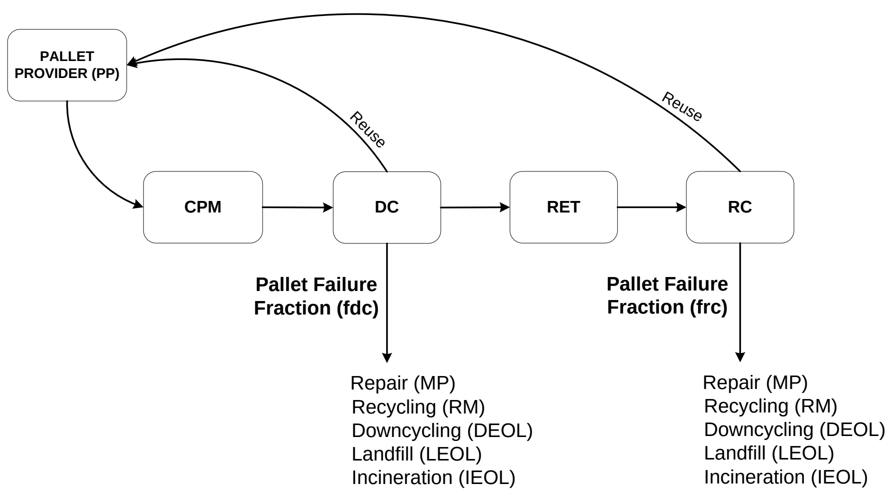


Figure 6. Pallet failure fraction

3.3.5 Pallet Costs

This section explains the costs associated with each pallet management system: buy/sell program and leased pools. A *purchase cost* applies to those pallets managed under a buy/sell program when Consumer Product Manufacturers (CPM) buy pallets from Pallet Manufacturers (MP). After use, the assumption is that these pallets are sold for a *selling price*.

L*easing cost* applies to pallets under leased pools (such as plastic and wooden pallets). This cost is usually broken into three components: an issue cost, which is a fixed cost per pallet ($/pallet), a rent cost per day, which will account for the days a pallet is being used in the system ($/pallet-day) and, a cost when transferred back to the pallet owner ($/pallet).

A *credit for return* is given to product distributors or retailers for sending pallets back to the pallet company owner. Product distributors may get charged a *transportation cost of return* by the pallet owner when returning their pallets after used.

In addition, a *transportation cost* per mile applies to all pallet management systems. This cost is usually calculated based on trucks' capacity for shipping loaded and unloaded pallets. Moreover, in the grocery industry, usually 48 ft. or 53 ft. trucks are used to transport products within facilities, which have an estimated shipping capacity of 24 loaded pallets or 480 unloaded pallets.

3.3.6 NOMENCLATURE

The following sets are used to define the mathematical programming model:

p = *Pallet management system; also referred as pallet type*
m = *Material (1, material type 1 for pallet p; and 2, material type 2 for pallet p)*
d = *Disposal scenario of damaged pallets (1, repair; 2, recycle; 3, downcycling; 4, landfill; and 5, incineration)*
t = *Time periods in weeks*

The parameters of the mathematical model are:

$W_{p,m,(i,j)}$ = *Weight of material m of pallet type p on arc (i,j) (lbs/pallet)*
$M_{p,m,(i,j)}$= *CO_2 footprint for material primary production per pound of material m per pallet type p in arc (i,j) (lbsCO_2/lb-pallet)*
$Mfg_{p,m,(i,j)}$ = *CO_2 footprint per pound of material m processed per pallet type p in arc (i,j) (lbsCO_2/lb-pallet)*
ET_p = *CO_2 footprint due to transportation per pallet type p per mile (lbsCO_2/mile-lb-pallet)*
$EOL_{p,m,(i,j)}$ = *CO_2 footprint per end-of-life scenario of material m for pallet type p in arc (i,j) (lbsCO_2/lb-pallet)*

$C_{o_{p,(i,j)}}$ = *Purchase/leasing cost of pallet type p on arc (i,j) ($/pallet)*

$CT_{p,(i,j)}$ = *Transportation cost per pallet type p per mile on arc (i,j) ($/mile-pallet)*

$S_{p,(i,j)}$ = *Credit for selling pallets type p or for returning empty leased pallets type p in arc (i,j) ($/pallet)*

$R_{p,d}$ = *End-of-life scenario fraction d per pallet type p (percent)*

fdc_p = *Failure fraction per pallet type p leaving DC (percent)*

frc_p = *Failure fraction per pallet type p leaving RC (percent)*

$Q_{p,i}$ = *Pre-positioned inventory of pallets type p at distribution center i (number of pallets)*

$L_{(i,j)}$ = *Distance traveled between nodes i and j (miles)*

$Dc_{i,t}$ = *Total demand at distribution center i at time t (number of pallets)*

$Db_{i,j,t}$ = *Total demand at retailer j from distribution center i at time t (number of pallets)*

Z = Minimum monetary costs

α = *Rate of cost increase (same α as in Algorithm) (percent)*

V = Large number of pallets

P = Number of pallet types in model

T = Number of time periods in model

$e_{p,m,(i,j)}$ = *Total life-cycle CO_2 footprint per pallet p in arc (i,j) (lbsCO_2)*

$C_{p,(i,j)}$ = *Total monetary cost per pallet type p in arc (i,j)*

3.3.7 OBJECTIVE FUNCTIONS COEFFICIENT DESCRIPTIONS

Coefficient ($) for System Cost Objective Function:

$$Cost = C_{Purchase/Leasing} + C_{Transportation} + C_{Selling\ Price/Pallet\ Credit}$$

$$C_{p,(i,j)} = C_{o_{p,(i,j)}} + CT_{p,(i,j)} * L_{(i,j)} - S_{p,(i,j)}$$

where,

$C_{o_{p,(i,j)}}$	$Purchase$ $/Leasing$:	Represents the purchase/leasing cost associated with each pallet management system.
$CT_{(i,j)} * L_{(i,j)}$	$Transportation$:	Illustrates the transportation cost for pallets shipped between nodes.
$S_{p,(i,j)}$	$Selling\ Price$ $/Pallet\ Credit$:	Illustrates the credit obtained by the distributor/retailer when empty pallets are either sold or returned to a pallet provider.

Coefficient (pounds of CO_2) for System Environmental Impact Objective Function:

$$Environmental\ Impact = EI_{Materials} + EI_{Manufacture} + EI_{Transportation} + EI_{End-of-life}$$

$$e_{p,m,(i,j)} = M_{p,m,(i,j)} * W_{p,m,(i,j)} + Mfg_{p,m,(i,j)} * W_{p,m,(i,j)} + ET_p * W_{p,m,(i,j)} * L_{(i,j)} + EOL_{p,m,(i,j)} * W_{p,m,(i,j)}$$

where,

$M_{p,m,(i,j)} * W_{p,m,(i,j)}$	$Materials$:	Represents the CO_2 footprint derived from the primary production of materials such as wood, plastic, and steel used for pallet manufacture on arc (i,j).
$Mfg_{p,m,(i,j)} * W_{p,m,(i,j)}$	$Manufacture$:	Represents the CO_2 footprint resulting from manufacturing pallets made of virgin and/or recycled materials (wood, plastic, and steel) on arc (i,j).
$ET_p * W_{p,m,(i,j)} * L_{(i,j)}$	$Transportation$:	Represents the CO_2 footprint resulting from shipping loaded and/or unloaded pallets on arc *(i,j)*.
$EOL_{p,m,(i,j)} * W_{p,m,(i,j)}$	$End\ of\ life$ $Scenarios$:	$Repair$, represents the CO_2 footprint of repairing wooden pallets (including steel nails recycling) on arc (i,j). $Reycling$, represents the CO_2 footprint resulting from recycling plastic pallets; includes recycling the plastic and the steel of their reinforcement bars, on arc (i,j). $Downcycling$, represents the CO_2 footprint resulting from downcycling wood (including steel nails recycling) on arc (i,j). $Landfill$, represents the CO_2 footprint resulting from sending pallets to landfill on arc (i,j). $Incineration$, represents the CO_2 footprint resulting from incinerating pallets (includes the CO_2 footprint of sending the steel of either the nails or the reinforcement bars to landfill) on arc (i,j).

3.3.8 Decision Variables

The model has the following decision variables:

$Y_{p,(i,j),t,t'}$ represents the number of pallets of type p that move from node i at time t to node j at time t'

$Inv_{p,i,t'}$ represents the pallet type p inventory at the distribution center i at time t'

$X_{p,i}$ binary variable that shows the unique pallet type p used by each consumer product manufacturer i

($X_{p,i} = 1$, if CPM i uses pallet type p; otherwise $X_{p,i} = 0$)

3.3.9 Model Logic

For each pallet type (in set *p*), is modeled its manufacture, procurement, use, and disposition (Figure 4). Each arc *(i,j)* in this network, models the transition of a pallet either from one stage in its life cycle to another or from one type of use to another as explained earlier, associating two attributes, $c_{i,j}, e_{i,j}$, with arc *(i,j)* to represent the monetary cost and environmental impact of such a transition.

To accommodate a multi-period planning horizon, time is included and the network is mapped to a time-space network with node set *N,* and arc set *A,* for each pallet type. A node in *N* will be of the form *(s,t),* where *s* represents a life cycle stage or use phase, such as "Raw Material," or, "Retailers," and *t* represents a period. Thus, when studying a planning horizon of one year divided into 52 one-week periods, *N* will contain 52 nodes of the form (*RM,t*), where *t* ranges between 1 and 52. Each of these nodes models the opportunity to extract raw material in week *t* for manufacture. Similarly, the time-space network will contain 52 nodes of the form (*MP,t), (CPM,t), …, (RC,t)*. An arc in *A* will be then of the form *(i,j)* = *((s,t),(s',t'))*, where *t'* >= *t*. For example, *A* will contain arcs of the form *((RM,t),(MP,t'))* that represent the extraction of raw materials in period *t* for manufacture in period *t'*. Figure 7 illustrates an example of the flow of a plastic pallet that is reused after its use. Arc *((RM,t),(MP,t))* represents the primary production of HDPE in period *t* for plastic pallet manufacture in *t.* Moreover, the pallet will be

shipped to distribution centers and retailers, represented by arcs *((CPM,t),(DC,t+1))* and *((DC,t+1),(MP,t+2))*, respectively. The pallet, after collected at the return center, will be reused *((RC,t+2),(CPM,t+3))*.

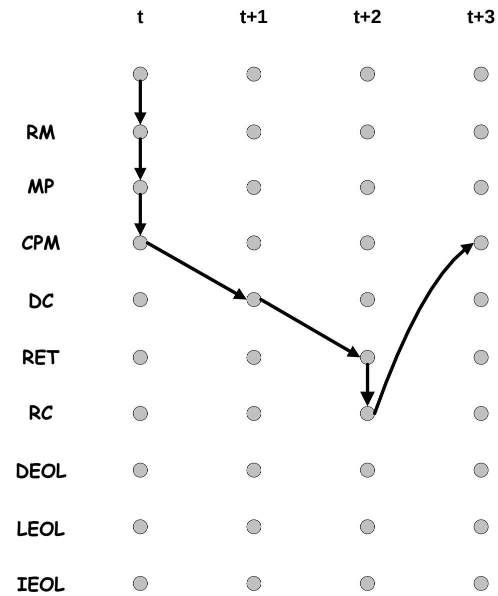


Figure 7. Pallet flow with end-of-life reuse

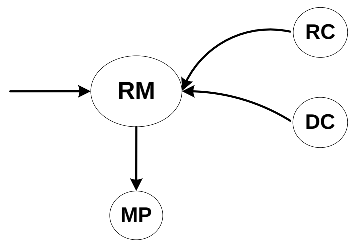
The need for pallets is modeled by assuming it is known with certainty how many pallets must flow on the arcs between nodes (*CPM,t)* and (*DC,t')* and between nodes (*DC,t)* and (*RET,t')* for all time pairs (*t,t')* where *t'* >= *t*.

It is assumed that the pallet management program dictates the end-of-life disposition of a pallet, which can represent fractions per end-of-life scenario from total pallets managed. Further, the weighted average of the costs and environmental impacts ($c_{i,j}, e_{i,j}$) associated with the potential pallet dispositions (end-of-life scenarios) is being modeled.

The finite lifespan of a pallet is included in the model indirectly by assuming that a fraction, fi_p, of pallets of type *p* leaving node *i* in the time-space network have in fact become unusable, and thus must leave the system and be replaced. Indexing this fraction by pallet type enables the modeling of different lifespans for pallets of different material. For example, the failure fraction for wooden pallets can be set much higher than the fraction for plastic pallets, hence, reflecting the different durabilities. Thus, for each pallet type, arcs of the form *((i,t),(EOL,t'))* in the arc set *A* will represent pallets failing at node *i* in period *t* and thus leaving the system and reaching their end-of-life in period *t'*. The system models pallet type and quantity decisions with the continuous and non-negative variables $Y_{p,(i,j),t,t'}$ that represent the number of pallets of type *p* that travel on arc *(i,j)* in the time-space network.

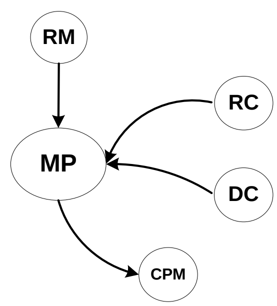
A detail explanation follows for all arcs in set *N*.

RAW MATERIAL



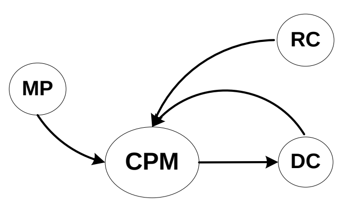
The raw material (RM) node models the opportunity to extract and produce virgin and recycled material for further pallet manufacture. Recycled material includes plastic and steel from damaged pallets used in previous time periods.

MANUFACTURED PALLET



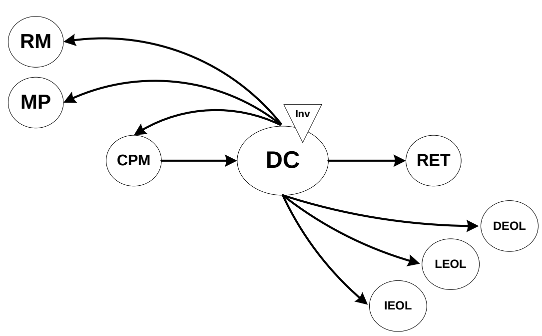
The manufactured pallet (MP) node models pallet manufacture with virgin and/or recycled material to be shipped to consumer product manufacturers. Further, manufactured pallets plus repaired wooden pallets coming from nodes DC and RC get shipped to CPM.

CONSUMER PRODUCT MANUFACTURER



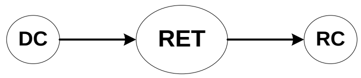
The CPM node models the opportunity of buying/leasing manufactured, repaired, and reused pallets from pallet providers by consumer product manufacturers.

DISTRIBUTION CENTER



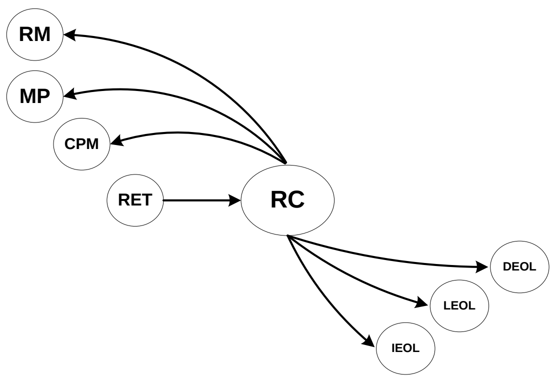
The DC node models the shipment of loaded pallets from CPM to DCs. Further, pallets used to fulfill the demand at the retailer leave DC and arrive at RET in the next time period. Some loaded pallets may stay in inventory, and a few empty and/or damaged pallets may be sold or sent back to pallet providers. Pallet providers will than send pallets to different locations depending on the pallet end-of-life scenario; damaged plastic pallets are sent to RM for recycling; damaged wooden pallets are sent to MP for repair; other wooden pallets are sent to DEOL for downcycling; some wooden and plastic pallets may end up in landfills (LEOL) or get incinerated (IEOL).

RETAILER



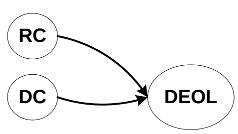
The RET node models loaded pallets being shipped from DC to RET. Empty pallets are then sent from RET to RC for collection and sorting.

RETURN CENTER



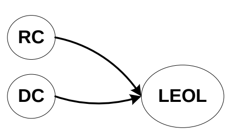
The RC node models the opportunity of collecting and sorting empty pallets coming from RET. Pallets are then sold or returned to pallet providers. Further, damaged plastic pallets are sent to RM for recycling; damaged wooden pallets are sent to MP for repair; other wooden pallets are sent to DEOL for downcycling; some wooden and plastic pallets may end up in landfills (LEOL) or get incinerated (IEOL).

DOWNCYCLING



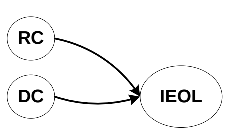
The DEOL node models the opportunity of downcycling damaged wooden pallets coming from DC and/or RC. Pallets leaving nodes DC and/or RC arrive at DEOL in the next time period.

LANDFILL



The LEOL node models the opportunity of sending wooden and/or plastic pallets coming from DC and/or RC to landfill. Pallets leaving nodes DC and/or RC arrive at LEOL in the next time period.

INCINERATION



The IEOL node models the opportunity of incinerating damaged wooden pallets coming from DC and/or RC. Pallets leaving nodes DC and/or RC arrive at IEOL in the next time period.

3.4 MATHEMATICAL PROGRAMMING MODEL

The mixed-integer programming model is a multi-objective and multi-period optimization model which minimizes monetary costs and environmental impact due to carbon dioxide (CO_2) emissions. The optimization model is defined in detail in this section.

<u>Objective Function: Minimizing System Monetary Cost</u>

$$Z = min_{Costs} = \min \sum_{p=1}^{P} \sum_{i\, in\, V} \sum_{j\, in\, V} \sum_{t} \sum_{t'} C_{p,(i,j)} * Y_{p,(i,j),t,t'} \quad for\; t' \leq t+1;\; t' \geq t \tag{1}$$

Objective function (1) calculates the system monetary cost, which includes the purchase/leasing cost, transportation cost, and the credit obtained for selling or returning a pallet after being used.

The feasible region *S* is defined as the variables values that satisfy the following set of constraints:

- *Constraint (2)* ensures that the sum of all pallets types shipped to each distribution center must fulfill their demand.

$$\sum_{p=1}^{P} \sum_{i=CPM} Y_{p,(i,DC),t,t+1} \geq Dc_{DC,t+1} \qquad \forall DC, t\; in\; T \tag{2}$$

- *Constraint (3)* ensures that the sum of all pallets shipped to each of the retailers must satisfy their demand.

$$\sum_{p=1}^{P} Y_{p(DC,RET),t,t+1} \geq Db_{DC,RET,t+1} \qquad \forall DC, RET, t\; in\; T \tag{3}$$

- Initial inventory must equal given value. *Constraint (4)* ensures a pre-inventory of pallets required to satisfy the first period demand at retailers.

$$Inv_{p,DC,0} = Q_{p,DC} \tag{4}$$

- *Constraint (5)* ensures damaged pallets leaving the DCs. A percentage of pallets shipped to the distribution centers are damaged and sent to repair, recycle, downcycle, landfill or incineration.

$$\sum_{k=DC}\sum_{j=G} Y_{p,k,j,t+1,t+2} \geq fdc_p * \sum_{i=CPM}\sum_{k=DC} Y_{p,i,k,t,t+1} \qquad \forall p \; in \; P, t \; in \; T \tag{5}$$

$$G = RM, MP, DEOL, LEOL, IEOL; DC = DC_1, DC_2 \ldots DC_n; \; CPM = CPM_1, CPM_2 \ldots CPM_n$$

- *Constraint (6)* ensures damaged pallets leaving the RCs. A percentage of pallets shipped to the return centers are damaged and sent to repair, recycle, downcycle, landfill or incineration.

$$\sum_{k=RC}\sum_{j=G} Y_{p,k,j,t+1,t+2} \geq frc_p * \sum_{i=RET}\sum_{k=RC} Y_{p,i,k,t,t+1} \qquad \forall p \; in \; P, t \; in \; T \tag{6}$$

$$G = RM, MP, DEOL, LEOL, IEOL; RC = RC_1, RC_2 \ldots RC_n; \; RET = RET_1, RET_2 \ldots RET_n$$

- *Constraint (7)* ensures damaged pallets from DCs disposed to one of the end-of-life scenarios. A percentage of damaged pallets leaving the DCs are sent to an end-of-life scenario (repair, recycle, downcycle, landfill, or incineration).

$$\sum_{k=DC} Y_{p,k,j,t+1,t+2} \leq R_{p,j} * fdc_p * \sum_{i=CPM}\sum_{k=DC} Y_{p,i,k,t,t+1} \qquad \forall j = RM, MP, DEOL, LEOL, IEOL; t \; in \; T \tag{7}$$

$$DC = DC_1, DC_2 \ldots DC_n$$

- *Constraint (8)* ensures damaged pallets from RCs disposed to one of the end-of-life scenarios. A percentage of damaged pallets leaving the RCs are sent to an end-of-life scenario (repair, recycle, downcycle, landfill, or incineration).

$$\sum_{k=RC} Y_{p,k,j,t+1,t+2} \leq R_{p,j} * frc_p * \sum_{i=RET} \sum_{k=RC} Y_{p,i,k,t,t+1} \qquad \forall j = RM, MP, DEOL, LEOL, IEOL; t \; in \; T$$

(8)

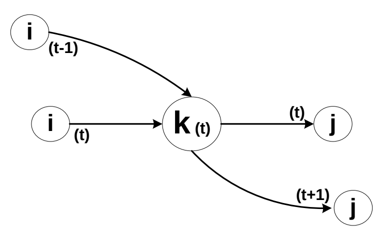
$$RC = RC_1, RC_2 \ldots RC_n$$

- Nodes balance constraints. *Constraint (9)* ensures a balanced flow of pallets for nodes RM, MP, CPM, RET, and RC. The number of pallets of type *p* entering the node must be equal to the number of pallets of type *p* departing the node.

$$\sum_{p=1}^{P} \sum_{i \; in \; V} Y_{p,(i,k),t-1,t} + \sum_{p=1}^{P} \sum_{i \; in \; V} Y_{p,(i,k),t,t} = \sum_{p=1}^{P} \sum_{j \; in \; V} Y_{p,(k,j),t,t} + \sum_{p=1}^{P} \sum_{j \; in \; V} Y_{p,(k,j),t,t+1} \qquad i \neq j; \; \forall t \; in \; T$$

$$\forall k = RM, MP, CPM, RET, RC$$

(9)



- Nodes balance constraints for DCs. *Constraint (10)* ensures a balanced flow of pallets for node DC. The number of pallets of type *p* entering the node plus taken from inventory must be equal to the number of pallets of type *p* departing the node and put in inventory.

$$Inv_{p,DC,t} + \sum_{p=1}^{P} \sum_{i \; in \; V} Y_{p,(i,k),t-1,t} + \sum_{p=1}^{P} \sum_{i \; in \; V} Y_{p,(i,k),t,t}$$
$$= \sum_{p=1}^{P} \sum_{j \; in \; V} Y_{p,(k,j),t,t} + \sum_{p=1}^{P} \sum_{j \; in \; V} Y_{p,(k,j),t,t+1} + Inv_{p,DC,t+1} \qquad i \neq j; \; k = DC; \; \forall t \; in \; T$$

(10)

- Set variables to zero:
  a. *Constraint (11)* ensures that wooden pallets do not get recycled.

$$Y_{p,(i,RM),t,t} = 0 \qquad p = 1,2,3\,;\ i = DC, RC; \forall t \ in \ T \tag{11}$$

  b. *Constraint (12)* ensures that plastic pallets do not get repaired, downcycled, or incinerated.

$$Y_{p,i,j,t,t} = 0 \qquad p = 4;\ i = DC, RC;\ j = MP, DEOL, IEOL; \forall t \ in \ T \tag{12}$$

- Only one specific pallet management system used by each CPM.
  a. *Constraint (13)* allows a very large number, if not unlimited number of pallets (under a specific and unique pallet management system per CPM) of type *p* to be manufactured. It also ensures that pallets are only used if system is chosen.

$$Y_{p,(MP,j),t,t} \leq V * X_{p,j} \qquad j = CPM; \forall p \ in \ P, t \ in \ T \tag{13}$$

  b. *Constraint (14)* makes sure that only one pallet management system is used per CPM.

$$\sum_{p=1}^{P} X_{p,i} = 1 \qquad i = CPM \tag{14}$$

  c. *Constraint (15)* represents pallets sent from DC back to reuse and which relate to a unique CPM.

$$Y_{p,(i,j),t,t+1} \leq V * X_{p,j} \qquad i = DC;\ j = CPM;\ \forall p \ in \ P, t \ in \ T \tag{15}$$

  d. *Constraint (16)* represents pallets sent from RC back to reuse and which relate to a unique CPM.

$$Y_{p,(i,j),t,t+1} \leq V * X_{p,j} \qquad i = RC;\ \ j = CPM;\ \forall p \ in \ P \tag{16}$$

Objective Function: Minimizing System Environmental Impacts (pounds of CO_2):

$$min_{Environmental_{Impacts}} = \sum_{p=1}^{P}\sum_{m=1}^{2}\sum_{i\,in\,V}\sum_{j\,in\,V}\sum_{t}\sum_{t'} e_{p,m,(i,j)} * Y_{p,(i,j),t,t'} + \sum_{p=1}^{P}\sum_{m=1}^{2}\sum_{i\,in\,V}\sum_{j\,in\,V}\left(M_{p,m,(i,j)} + Mfg_{p,m,(i,j)}\right) * W_{p,m,(i,j)} * Q_{p,i} \qquad for\ t' \leq t+1;\ t' \geq t$$

(17)

Objective function (17) calculates the system environmental impacts to satisfy pallet demand and listed constraints.

Subject to:

- All previous constraints: (2), (3),… (16) plus:
- Satisfy minimum system cost. *Constraint (18)* limits the system cost to not be greater than the minimum cost. This constraint is parameterized with α, allowing different cost increases for further analysis.

$$\sum_{p=1}^{P}\sum_{i\,in\,V}\sum_{j\,in\,V}\sum_{t}\sum_{t'} C_{p,(i,j)} * Y_{p,(i,j),t,t'} \leq Z * (1+\alpha)$$

(18)

The multi-objective optimization model first finds the set of pallet decisions that minimize the system cost and then finds the set of pallet decisions that are the least environmentally harmful. The output of the first objective function forms part of a cost constraint when minimizing the environmental impact; which allows restricting the cost to be less or equal than the minimum cost. Additionally, this cost constraint is parameterized, allowing relaxation of the system cost if desired (with parameter α). The model generates multiple decisions, allowing the decision-maker to choose the tradeoff that fits their company's goals. Likewise, the priority objective functions can also be exchanged, minimizing first the environmental burden, and then the total costs constrained by these environmental costs.

3.5 Input Data Collection

Input data for pallet materials, manufacturing processes, and pallet end-of-life scenarios are explained in this section.

Materials

For the purposes of this work wooden pallets are made of two types of materials: hardwood-oak for the pallet structure (boards and blocks), and low alloy steel for the nails. On the other hand, the body of plastic pallets is made off high-density polyethylene (HDPE) with low carbon steel reinforcement bars (PCRS, 2000).

Table 3 shows the carbon dioxide footprint from materials primary production, such as wood, plastic, and steel, used later for pallet fabrication. The CO_2 footprint refers to the mass of carbon dioxide (CO_2), in pounds, produced and released into the atmosphere, as a consequence of the production of one pound of the material (CES, 2010). The materials database from the Cambridge Engineering Selector (CES) 2010 was selected as the main source for these materials impacts. The following assumptions were made for each material: hardwood-oak medium density; Zinc-Copper alloy, fastener wire, for low alloy steel; high-density homopolymer for the HDPE; and, AISI 1010, annealed, for low carbon steel.

Table 3. Carbon dioxide footprint from material primary production

		MATERIAL CO_2 Footprint
	Material	**lbs CO2/lb**
Wood Pallet	Hardwood Oak: medium density	0.4495
	Low Alloy Steel: Zn-Cu alloy, fastener wire	4.5800
Plastic Pallet	HDPE: high-density homopolymer	2.0500
	Low Carbon Steel: AISI 10101, annealed	2.4850

Manufacture

The fabrication of wooden pallets includes assembly and construction of wood boards, and casting for the production of nails. Injection molding is assumed for the fabrication of plastic pallets, and extrusion for their reinforcement bars (PCRS, 2000). Table 4 shows the CO_2 footprint associated with pallet manufacture.

Table 4. Carbon dioxide footprint from pallet manufacture

	Material	Manufacturing Process	MANUFACTURE CO_2 Footprint lbs CO_2/lb
Wood Pallet	Hardwood Oak	Assembly and Construction	0.0400
	Low Alloy Steel	Casting	0.0669
Plastic Pallet	HDPE	Injection Molding	0.5165
	Low Carbon Steel	Extrusion	0.2645

Transportation

For this research it was assumed the use of a model year 2007 or later Class 8 tractor trailer, which has a fuel economy of 6 mpg when loaded. The assumed fuel is on-road diesel fuel with an energy content of 128,450 Btu/gal, a mass density of 3170 g/gal, and a carbon fraction of 86 percent (Comer et al., 2010). The following conversion was used:

$$\frac{gr\ CO_2}{mile} = \frac{\rho * CF * 3.67}{mpg} \rightarrow \frac{gr\ CO_2}{mile} * \frac{1\ lb}{454\ gr} = \boldsymbol{\frac{lbs\ CO_2}{mile}}$$

Eq. 19

where,

ρ = mass density of fuel in grams of fuel per gallon (3167 gr/gal)

CF = carbon content of fuel (86 percent)

3.67 = CO_2 to Carbon ratio (44/12)

mpg = miles per gallon (6 miles/gal)

454 = conversion factor to convert grams per pounds

Substituting for the given values, the following equation shows the carbon dioxide emitted per truck per mile traveled.

$$\frac{gr\ CO_2}{mile} = \frac{3167 gr/gal * 0.86 * 3.67}{6} * \frac{1\ lb}{454\ gr} = \mathbf{3.67}\ \frac{\mathbf{lbs\ CO_2}}{\mathbf{mile}}$$

Furthermore, the total amount of CO_2 released per truck load of pallets per mile traveled is:

$$3.67\ \frac{lbs\ CO_2}{mile} * \frac{1}{W * LPT}$$

Eq. 20

where,

W = pallet weight (lbs/pallet)

LPT = number of pallets in load per truck

Therefore, the CO_2 footprint per pallet per mile traveled is calculated by substituting the pallet weight (W) and the number of pallets in load per truck (LPT), which may vary if shipping loaded or unloaded pallets.

<u>End-of-Life Alternatives</u>

Pallets may be disposed according to different scenarios. Each pallet end-of-life may include different material disposal scenarios. These scenarios are detailed below:

- Reuse: does not create any additional CO_2 footprint in the end-of-life stage.
- Repair: only applied to wooden pallets. This scenario refers to repairing the wood and recycling the nails which are made of steel. It has been assumed that for repairing processes 90 percent of the material, in this case wood, is being recovered (Ashby, 2009), which means the environmental impact accounts for 10 percent of the material CO_2 footprint of each pallet (only their wood).
- Recycle: only applied to plastic pallets. This scenario refers to recycling the plastic and recycling the steel reinforcement bars. The CO_2 footprint refers to the mass of carbon dioxide (CO_2), in pounds, produced and released into the atmosphere, as a consequence of recycling one pound of the material (CES, 2010).
- Downcycle: only applied to wooden pallets. This scenario includes downcycling the wood and recycling the nails made of steel. Since downcycling allows the creation of by products such as mulch and animal bedding, it has been assumed that this process releases 40 percent of the total CO_2 released for the wood production. Thus, 60 percent of the material carbon dioxide footprint for wood is being saved. Therefore, the CO_2 footprint associated with downcycling the wood is being calculated by multiplying 0.40 times the pounds of CO_2 released when processing hardwood/softwood.
- Landfill: when products are sent to landfill the recovery factor is neglible (Ashby, 2009), which means the environmental impact is represented by 100 percent the carbon dioxide footprint for material primary production.
- Incineration: pallets may get incinerated creating a high carbon footprint. This scenario includes incinerating the wood and sending the steel (from nails) to landfill.

Table 5 shows the CO_2 footprint associated to the different material disposal scenarios.

Table 5. Carbon dioxide footprint per material disposed

		MATERIAL DISPOSAL				
		Wood Repair	Plastic and Steel Recycling	Wood Downcycling	Landfill (wood, plastic and steel)	Incineration (wood and plastic)
	Material	lbs CO2/lb	lbs CO2/lb	lbs CO2/lb	lbs CO2/lb	lbs CO2/lb
Wood Pallet	Hardwood Oak	0.04495	N/A	0.18	0.4495	1.7350
	Low Alloy Steel	N/A	0.8235	N/A	4.5800	N/A
Plastic Pallet	HDPE	N/A	0.5000	N/A	2.0500	3.1400
	Low Carbon Steel	N/A	0.6950	N/A	2.4850	N/A

Figure 8 shows the CO_2 footprint of each end-of-life scenario per pound of material for wood pallets (only considering the wood) and plastic pallets (only taking into account the plastic for graph purposes). Repair releases the least amount of CO_2; while recycling is the more sustainable option for plastic pallets. Also, sending pallets to landfill or incineration will create the highest carbon footprint among the scenarios. Note that this graph only illustrates the environmental impact of each end-of-life scenario per pound of material per pallet type and does not include the pallet lifespan.

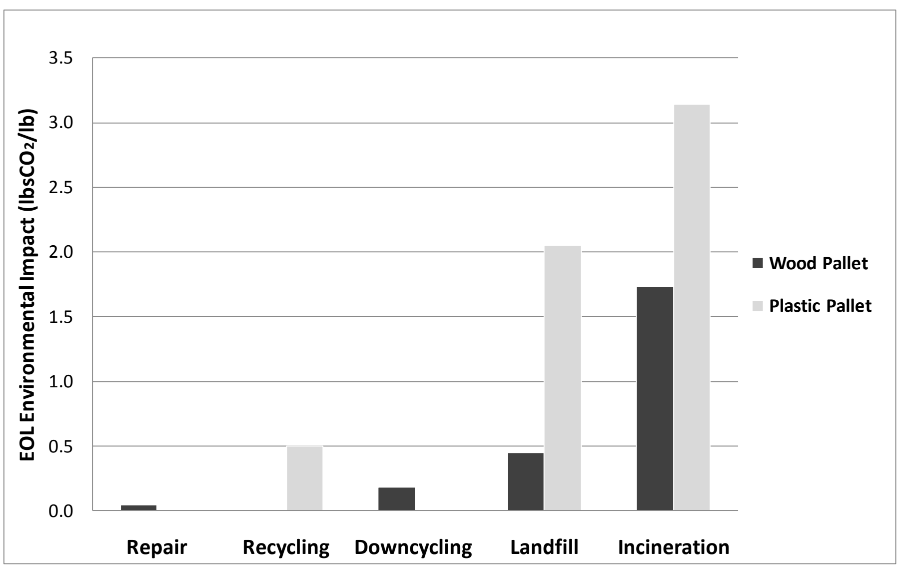


Figure 8. Environmental impact per end-of-life scenario per pound of material per pallet type

CHAPTER IV

VALIDATION

The purpose of this section is to validate the proposed model in Figure 4 - Chapter III. Typically, validation would involve experimenting real data to see how well the model represents the actual system and to further compare the results obtained through the model with real data of the system. However, because real data on the carbon footprint from pallet operations in a supply chain is not available, the validation proposed in this work is formulated differently. Therefore, a series of statements on hypothesis for which the system behavior was known were tested and used as a tool for supporting the logic of the system being modeled.

4.1 ASSUMPTIONS

The model is validated studying four different pallet management systems (or pallet types). Pallet type 1 is managed under a buy/sell program, and pallet types 2, 3, and 4 are pallet leasing companies. Pallet types 1, 2, and 3 are wooden pallets; and pallet type 4 is a plastic pallet. They differ from one another in weight, cost, and end-of-life scenarios.

- <u>Pallet type 1</u>: Pallet ownership is transferred with the product. Pallet type 1 is made of hardwood and weighs 45 pounds. This pallet provider does not repair or recycle pallets. The product distributor gains credit for selling these pallets after they have been used.
- <u>Pallet type 2</u>: Hardwood pallet under pooling system; ownership is not transferred with the pallet. Type 2 pallets weigh 65 pounds. The pallet provider 2 repairs pallets, and sends wood waste to

recycling centers. This pallet provider charges for returning their pallets from the product distributor's facilities back to their depots.

- Pallet type 3: Hardwood pallet under pooling system; ownership is not transferred with the pallet. Type 3 pallets weigh 62 pounds. The pallet provider repairs pallets and sends wood waste to recycling centers.
- Pallet type 4: Plastic pallet under pooling system; ownership is not transferred with the pallet. Type 4 pallets weigh 47.5 pounds. The pallet provider 4 recycles their pallets when damaged. The product distributor obtains a credit for returning these pallets back to the pallet provider.

A summary of pallet types characteristics are illustrated in Table 6. In this table the column Logistics defines if the pallet type is managed under a buy/sell program or a leased pool. Pallet Lifespan is the fraction of pallets per cycle that in fact have become unusable, and thus must leave the system. Material and Manufacturing Processes are directly related with the pallet fabrication; and the End-of-life Percentage represents the fraction of damaged pallets leaving the distribution centers and retailers that reach each end-of-life scenario (such as repair, recycle, downcycle, landfill, or incineration). In addition, the CO_2 footprint from material primary production, manufacture, transportation, and each end-of-life scenario per pallet type are detailed in Appendix A.

Table 6. General management characteristics per pallet type

PALLET TYPE	LOGISTICS	WEIGHT (lbs)	PALLET LIFESPAN FRACTION	MATERIAL	MANUFACTURING PROCESS	END-OF-LIFE PERCENTAGE				
						Repair	Recycling	Downcycling	Landfill	Incineration
Pallet 1	Wood Buy/Sell Program	45	1/3	Pallet: Hardwood Oak Nails: Low Alloy Steel	Assembly & Construction/ Casting	10%	N/A	89%	1%	0%
Pallet 2	Wood Pooled	65	1/23	Pallet: Softwood Pine Nails: Low Alloy Steel	Assembly & Construction/ Casting	80%	N/A	19%	1%	0%
Pallet 3	Wood Pooled	62	1/23	Pallet: Hardwood Oak Nails: Low Alloy Steel	Assembly & Construction/ Casting	80%	N/A	19%	1%	0%
Pallet 4	Plastic Pooled	47.5	1/80	Pallet: HDPE Reinforcement bars: Low Carbon Steel	Injection Molding/ Casting	N/A	100%	N/A	0%	0%

Other assumptions for the analysis include:

- All consumer product manufacturers are collapsed into one single node because the volume of products supplied by each consumer product manufacturer to each distribution center is not known;
- The use phase has eight (8) distribution centers, seventy five (75) retailers, and a single return center;
- A deterministic demand, estimated on a weekly basis, is assumed at each distribution center and each retailer;
- There is an unlimited number of new pallets that can be manufactured;
- All wooden pallets are assumed to use 150 nails (http://www.chep.com). Paint is not considered to be used in wooden pallets;
- Pallet fabrication takes place in each of the pallet providers facilities and all material waste is used for fabrication. As a result, all wood and recycled plastic is used in production of new pallets;
- The same carbon dioxide footprint applies when manufacturing pallets made of raw or recycled plastic;
- All pallet manufacturers are located in the U.S.;
- When pallets are repaired or recycled, a supply of new pallets for replacement is readily available;
- Truck service is readily available and is the only transportation mode used;
- A load per truck is considered to take 480 unloaded pallets or 24 loaded pallets;
- Transportation costs remain constant throughout the period in study;
- Transportation is only considered between product distributor's facilities (among distribution centers, retailers and the return center);
- Residence time of a leased pallet is 30 days;
- The system starts with a pre-inventory of 34,000 type 1 pallets in order to satisfy pallet demand at retailers in period 1.

4.2 VALIDATION

The mathematical programming model was validated with data gathered from a case study of an existent grocery supply chain network. Then, systematic experimentation was conducted to verify if the model was constructed in a logical manner and included all the factors to be considered. The algorithm was run for different scenarios by changing the inputs of the model in order to determine if the outputs obtained were logical. A series of different hypotheses for which system behavior was known before hand were posed and tested. Different results are shown in order to validate the logic of the system and to ensure that the results are aligned with the system being modeled.

Validation when the objective function is minimization of environmental impacts

The results in Tables 7 and 8 are used for validation purpose to compare against other hypotheses to validate the optimization model when minimizing the total system environmental burden. These results are referred to throughout this section as *environmental base scenarios*, because they were obtained by using the real input data per pallet type, as for materials, costs, etc.

As seen in Tables 7 and 8, pallets type 3 are preferred in the system, representing 86 percent and 92 percent of total pallet runs required to satisfy the demand for a time horizon of 6 months and 1 year, respectively. Pallets type 1 are used in smaller quantity, representing only 14 percent for a time horizon of 6 months, and 8 percent for a time horizon of 1 year, while pallets type 2 and 3 are not selected to be used. The pallet percentage varies from one time horizon to another since the longer the time frame is the more pallets type 1 (in pre-inventory) are discarded. As a result, more pallets are required to be manufactured while the time horizon is longer. A pallet run refers to the pallet use per cycle to satisfy the pallet demand. This pallet can be a new, reused, or repaired pallet.

Table 7. Environmental base scenario - Number of pallets required to satisfy demand when minimizing environmental impacts (Time horizon: 6 months)

Total System Environmental Impact:	7,607,473	lbs CO_2
	3,458	Metric Tons CO_2

NUMBER OF PALLETS							
Pallet Type	**New (Manufactured)**	**Reused w/o Repair**	**Repaired to Reuse**	**Recycled to Reuse**	**Initial Inventory**	**Number of pallet runs to satisfy demand**	**Pallet Type %**
Pallet 1	-	95,618	2,300	-	34,000	**131,918**	**14%**
Pallet 2	-	-	-	-	-	-	0%
Pallet 3	100,406	663,661	24,309	-	-	**788,376**	**86%**
Pallet 4	-	-	-	-	-	-	0%
	Total number of pallet runs to satisfy demand for a time horizon of 6 months:					**920,294**	

Table 8. Environmental base scenario - Number of pallets required to satisfy demand when minimizing environmental impacts (Time horizon: 1 year)

Total System Environmental Impact:	10,291,815	lbs CO_2
	4,678	Metric Tons CO_2

NUMBER OF PALLETS							
Pallet Type	**New (Manufactured)**	**Reused w/o Repair**	**Repaired to Reuse**	**Recycled to Reuse**	**Initial Inventory**	**Number of pallet runs to satisfy demand**	**Pallet Type %**
Pallet 1	-	122,450	2,513	-	34,000	**158,963**	**8%**
Pallet 2	-	-	-	-	-	-	0%
Pallet 3	109,433	1,615,300	57,209	-	-	**1,781,942**	**92%**
Pallet 4	-	-	-	-	-	-	0%
	Total number of pallet runs to satisfy demand for a time horizon of 1 year:					**1,940,904**	

As a result, one can conclude that pooled wooden pallets (type 3) are the preferred pallets because they last the longest among wooden pallets (type 1, 2 and 3), weigh the least among pooled wooden pallets (type 2 and 3), and are repaired in high percentage (80 percent of total damaged pallets). The hypotheses/statements used to validate the model are presented below.

- *Statement 1: Would pallets type 4 be chosen if the CO_2 footprint from plastic primary production is equal to the CO_2 footprint from wood primary production (changing parameter $M_{p,m,(i,j)}$)?*

Predicted behavior: Pallet type 4 would not be chosen because the CO_2 footprint from manufacturing processes is very high compared to the CO_2 footprint from assembly and construction as for wooden pallets.

Model results: Pallet type 4 does not appear to be chosen as the preferred option. As shown in Table 9, pallets type 3 would still be the only type manufactured. These outcomes are the same as the *environmental base scenarios.*

Table 9. Statement 1 – Analysis of CO_2 footprint from plastic production

		Base Scenario: CO_2 footprint from plastic production = 2.05 lbsCO_2/lb		Scen. Stat. 1: CO_2 footprint from plastic production = 0.4495 lbsCO_2/lb	
Time Horizon		**6 months**	**1 year**	**6 months**	**1 year**
Total System Environmental Impact (metric Tons CO_2)		**3,458**	**4,678**	**3,458**	**4,678**
Number of New Pallets Manufactured	**Pallet 1**	-	-	-	-
	Pallet 2	-	-	-	-
	Pallet 3	100,406	109,433	100,406	109,433
	Pallet 4	-	-	-	-

- *Statement 2: Would pallets type 4 be chosen if the CO_2 footprint from making plastic pallets would equal the CO_2 footprint from making wooden pallets (changing parameter $Mfg_{p,m,(i,j)}$)?*

Predicted behavior: Pallet type 4 would not be chosen as preferred since the CO_2 footprint from material primary production is very high compared to the CO_2 footprint from wood primary production.

Model results: As shown in Table 10, pallet type 4 would not be manufactured. Pallet type 3 would be chosen to be manufactured in the same amount as the *environmental base scenario.*

Table 10. Statement 2 – Analysis of CO_2 footprint from plastic pallet manufacture

		Base Scenario: CO_2 footprint from plastic pallet manufacture = 0.5165 lbsCO2/lb		Scenario Stat. 2: CO_2 footprint from plastic pallet manufacture = 0.04 lbsCO2/lb	
Time Horizon		6 months	1 year	6 months	1 year
Total System Environmental Impact (metric Tons CO_2)		3,458	4,678	3,458	4,678
Number of New Pallets Manufactured	Pallet 1	-	-	-	-
	Pallet 2	-	-	-	-
	Pallet 3	100,406	109,433	100,406	109,433
	Pallet 4	-	-	-	-

Table 11 shows the CO_2 footprint from materials production and pallet manufacturing processes for each pallet type. The CO_2 footprint from material and manufacture life-cycle stages of plastic pallets (123.58 lbsCO$_2$/lb) is much higher compared to the CO_2 footprint of material and manufacture life-cycle stages of wooden pallets (which range between 34.50 and 44.29 lbsCO$_2$/lb for pallet type 1 and type 2, respectively). This corroborates why plastic pallets may not be chosen to optimize the system in questions 1 and 2.

Table 11. CO_2 footprint from material and manufacture life-cycle stages per pallet type

Pallet Type/ Material		Material (lbsCO2/lb)	Manufacture (lbsCO2/lb)	Total CO_2 footprint from material production and pallet manufacture (lbsCO2/lb)
1	Wood	32.62	1.88	34.50
2	Wood	41.61	2.68	44.29
3	Wood	40.26	2.56	42.82
4	Plastic	101.35	22.23	123.58

- *Statement 3 - Part A: The answers to questions 1 and 2 imply that neither the CO_2 footprint from plastic production[5] nor the CO_2 footprint from plastic pallet manufacturing, individually, make a difference on the total system environmental impact. However, the following question arises: would pallets type 4 be chosen if both the CO_2 footprint from material production and the CO_2 footprint from pallet manufacturing processes are simultaneously changed?*

[5] The material embodied energy is commonly expressed as $(Hm)_x$ by Ashby (2009). For Figure 12 purposes the expression $(Hm+P)_x$ is used for material primary production and process CO_2 footprint, where x=p represents plastic , and x=w represents wood.

Predicted behavior: Pallet type 4 would be chosen when the CO_2 footprint from material primary production and from pallet manufacture is equal for wooden and plastic pallets. This output is expected because pallet type 4 last the longest and is reused more times, creating a low environmental impact.

Model results: Figure 9 illustrates the trend of pallets type 4 in the system. The lower the CO_2 footprint from plastic production plus the CO_2 footprint from plastic pallet manufacture, the higher the proportion of these pallets in the system. Different scenarios for the CO_2 footprint of plastic production plus manufacturing processes are illustrated in Figure 9.

Line A in Figure 9 represents the scenario when the CO_2 footprint of plastic production and plastic pallet manufacture equals the CO_2 footprint of wood processing and wood pallet fabrication. In this scenario pallet type 4 (plastic) starts to be manufactured after 5 months, and represent 73 percent of total new pallets manufactured for a time horizon of 6 months, while the remaining are pallets type 3. As mentioned earlier in the study, the longer the time span, the higher the percentage of pallets type 4 in the system since they last longer and can get reused more times, offsetting the CO_2 footprint from fabricating new pallets. As a result, pallets type 4 represent 100 percent of total new pallets manufactured after a time horizon of 9 months.

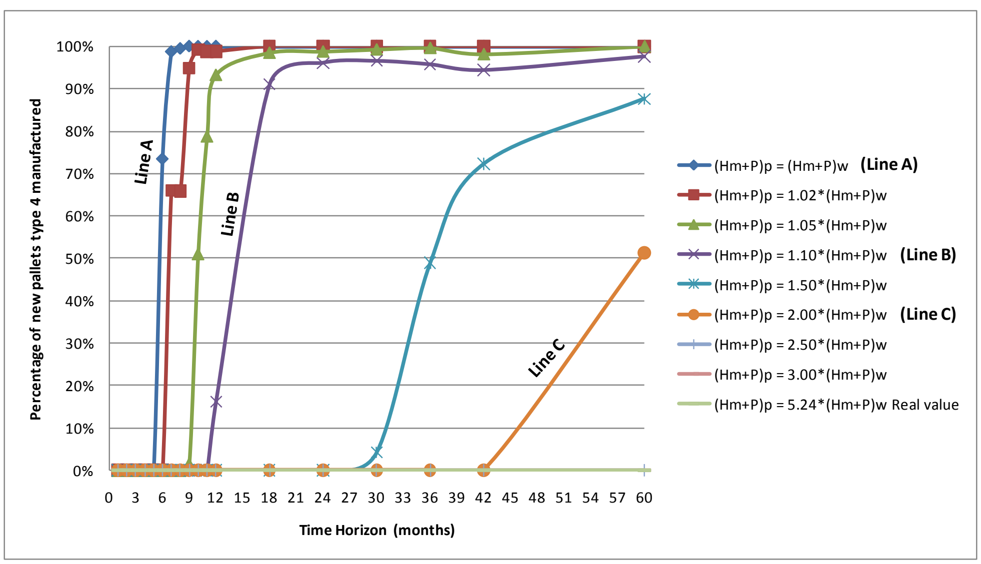


Figure 9. Statement 3 Part A – CO_2 footprint analysis for material and manufacture phases of pallet type 4

Other scenarios study different CO_2 footprints for plastic pallets. For example, Line B in the figure represents the scenario when plastic pallets have a total CO_2 footprint for plastic production and plastic pallet manufacture 1.10 times the CO_2 footprint of wood production and wooden pallet fabrication together. In this scenario, pallets type 4 start to be manufactured after an 11 month time horizon, representing only 16 percent of the total new pallets manufactured for a time horizon of 12 months. For a time horizon of 18 months pallets type 4 represent 90 percent of total pallets manufactured.

In summary, the lower the CO_2 footprint from plastic production and plastic pallet manufacture, the higher the percentage of these pallets in the system. The results are expected since pallet type 4 has the longest lifespan within the pallets in study. Moreover, pallets type 4 with high CO_2 footprint from material production and manufacture are preferred only for long time horizons.

- *Statement 3 - Part B: Under the assumption that a plastic pallet has the same CO_2 footprint in the material and manufacture life-cycle stages as a wood pallet (Line A in Figure 9), the two following hypotheses are analyzed:*

1) *If the model runs for a time horizon of 3 months with only plastic pallets type 4, the total system environmental impact will be higher than if only wooden pallets type 3 are manufactured.*

Predicted behavior: That the system environmental impact will increase because the CO_2 footprint from using plastic pallets of type 4 is higher than the CO_2 footprint from using wooden pallets type 3.

Model results: As shown in Figure 10, when only pallet type 4 is manufactured the total environmental impact of the supply chain increases to 6.65 metric KTons of CO_2 (S in figure), compared to 2.85 metric KTons of CO_2 when pallet type 3 is chosen. As a result, the CO_2 footprint increases by 233%. This result is expected because for a short time horizon long lasting pallets are not needed.

2) *If the model runs for a time horizon of 12 months with only wooden pallets type 3, the total system environmental impact will be lower than if only plastic pallets type 4 are manufactured.*

Predicted behavior: That the system environmental impact will decrease because the CO_2 footprint from using pallets of type 3 is lower than the CO_2 footprint from using pallets of type 4.

Model results: As shown in Figure 10, when only pallet type 3 is manufactured the total environmental impact of the supply chain decreases to 4.31 metric KTons of CO_2 (V in figure), compared to 4.60 metric KTons of CO_2 when pallet type 4 is chosen.

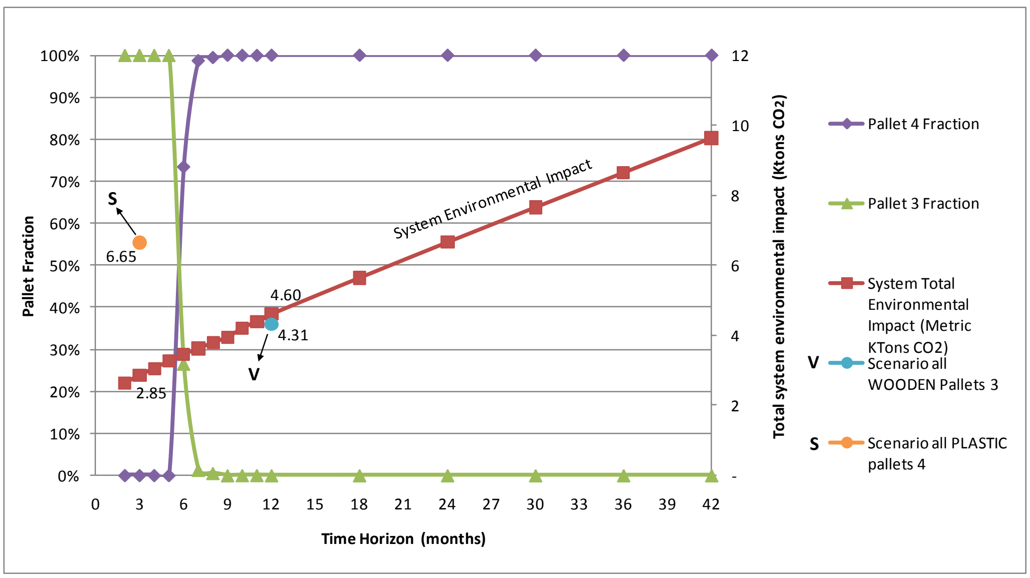


Figure 10. Statement 3 – Part B - Pallet fraction used when the CO_2 footprint from plastic primary production and plastic pallet manufacture equal the CO_2 footprint from wood primary production and wood pallet manufacture

- *Statement 4: Would pallets of type 3 represent the highest proportion of new pallets manufactured if their failure fraction (fi_p) per cycle would increase from 1/23 to 1/3 (same as failure fraction of pallet type 1)?*

Predicted behavior: Pallet type 3 would not be chosen because they weigh more than pallet type 1(65 lbs/pallet compared to 45 lbs/pallet) and because their failure fraction would be high, creating a higher total environmental impact.

Model results: Pallets type 3 would not optimize the system if they have such a short lifespan as shown in Table 12. Instead, pallets of type 2 are the only type manufactured.

Table 12. Statement 4 – Analysis of pallet type 3 failure fraction

		Base Scenario: Pallet 3 failure fraction per cycle = 1/23		Scenario Stat.4: Pallet 3 failure fraction per cycle = 1/3	
Time Horizon		6 months	1 year	6 months	1 year
Total System Environmental Impact (metric Tons CO_2)		3,458	4,678	3,528	4,758
Number of New Pallets Manufactured	Pallet 1	-	-	-	-
	Pallet 2	-	-	100,406	109,433
	Pallet 3	100,406	109,433	-	-
	Pallet 4	-	-	-	-

- *Statement 5: Pallets type 3 will be the only type manufactured if the model runs with only pallets type 2 and type 3. (Note: assuming under this scenario same pre-inventory of both pallet types).*

Predicted behavior: Pallets type 3 would be preferred because they weigh less than pallets type 2 and have the same lifespan, creating a lower total environmental impact.

Model results: Only pallets of type 3 are manufactured.

Table 13. Statement 5 – Only pallets type 2 and type 3 in the system

Time Horizon		6 months	1 year
Total System Environmental Impact (metric Tons CO_2)		3,153	4,333
Number of New Manufactured Pallets	Pallet 2	-	-
	Pallet 3	82,258	89,668

- *Statement 6 - Part A: Fewer pallets should be manufactured if the initial inventory (pre-inventory at the distribution centers) is represented by only plastic pallets type 4 instead of wooden pallets type 1 (Note: $Q_{p,i}$= 34,000 pallets).*

Predicted behavior: Less number of pallets should be manufactured when starting with an inventory of pallets type 4, due to their long lifespan compared to pallets type 1.

Model results: When the system starts with plastic pallets in pre-inventory, fewer new pallets are needed to satisfy the demand (refer to Table 14, column Scenario Statement A). A total of 85,158 instead of 109,433 pallets are manufactured for a time horizon of 1 year. The difference between the total numbers of pallets manufactured is expected because plastic pallets last 80 cycles compared to pallets type 1 which last 3 cycles.

Also, pallets have to be manufactured during the first week in order to satisfy the demand at the distribution centers. Pallets type 3 are manufactured to fulfill such demand because their low environmental impact and high lifespan. Furthermore, a small amount of pallets type 1 (1,996 pallets) are manufactured during the last weeks of the 1 year time horizon; these pallets are chosen because they will be used only for a few weeks, and have the lowest total CO_2 footprint among the pallets in the study.

- *Statement 6 - Part B: Plastic pallets type 4 should be preferred when the pre-inventory has 160,000 pallets type 4 (an excess amount of pallets included in the system above the pallet amount needed to satisfy demand at week 1).*

Predicted behavior: When starting with an excess inventory of pallets type 4 this should be enough to satisfy the pallet demand for a 1 year time horizon, since these pallets last approximately 80 cycles (more than 4 years) before damaged. Note that pre-inventory exists only at the DCs and will satisfy the demand at the retailers. Furthermore, the plastic pallets in pre-inventory cannot be returned to satisfy the first week's demand at distribution centers. For this reason, it is predicted that pallets will be manufactured to satisfy the demand only of week 1.

Model results: The pre-inventory of pallets type 4 are mainly used to fulfill the pallet demand during 1 year. However, the system only manufactures pallets at the beginning of the time horizon to fulfill the total demand at the distribution centers in week 1, as shown in Table 14 Scenario Statement B. For this reason, the system chooses to manufacture 33,582 pallets type 1 in order to satisfy the demand at the DCs in a week.

Table 14. Statement 6 – Analysis of pallet type in pre-inventory

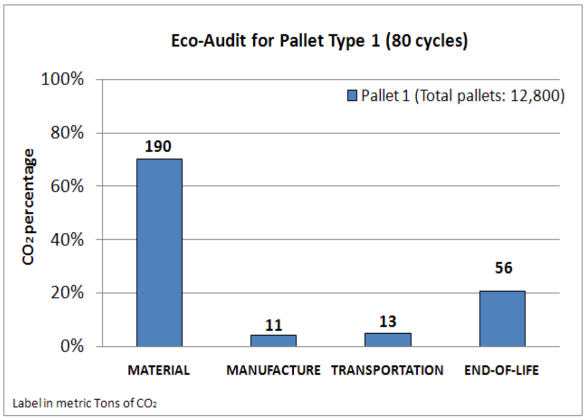
Time Horizon: 1 year		Base Scenario: pre-inventory pallets type 1 (34,000)	Scenario Stat. 6A pre-inventory pallets type 4 (34,000)	Scenario Stat. 6B pre-inventory pallets type 4 (160,000)
Total System Environmental Impact (metric Tons CO_2)		**4,678**	**5,552**	**10,509**
Number of New Manufactured Pallets	Pallet 1	-	1,996	33,582
	Pallet 2	-	-	-
	Pallet 3	109,433	83,162	-
	Pallet 4	-	-	-
	Total	**109,433**	**85,158**	**33,582**

<u>Eco-audit per pallet type</u>

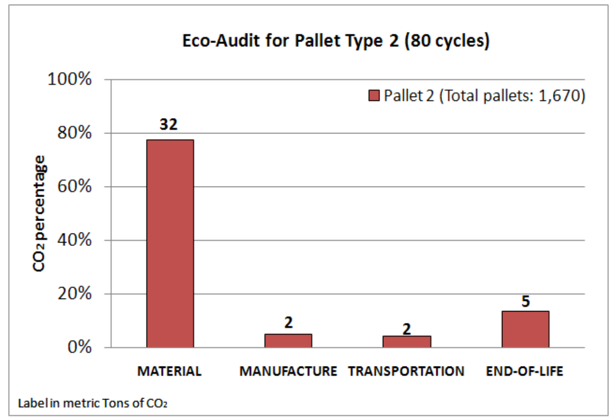
An eco-audit was developed in this section to corroborate the importance of the environmental impact of materials life-cycle stage within all four life-cycles stages. The eco-audit tool allows designers to quickly estimate which life-cycle stage causes the most damage to the environment to focus their design efforts on the most significant life phases (Ashby, 2009). The validation, when minimizing the environmental impacts, shows the sensitivity of the model when modifying the CO_2 footprint from materials production and pallets manufacture. In addition, it helps to visualize and compare the total CO_2 footprint of the four pallet types in the study.

The functional unit for performing the eco-audit was defined as the number of pallets required to fulfill a demand of 480 pallets per cycle for a time horizon of 80 cycles and assuming a total transportation of 300 miles. The eco-audit studies the environmental impact of each pallet type when satisfying that

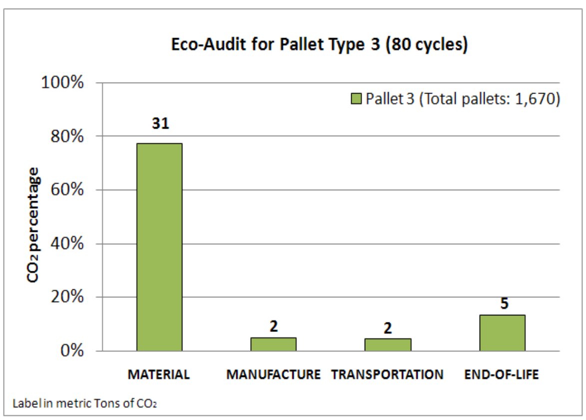
functional unit (refer to Figure 11). Note the assumptions are used only for the purpose of this analysis; they do not apply for the mathematical programming model.



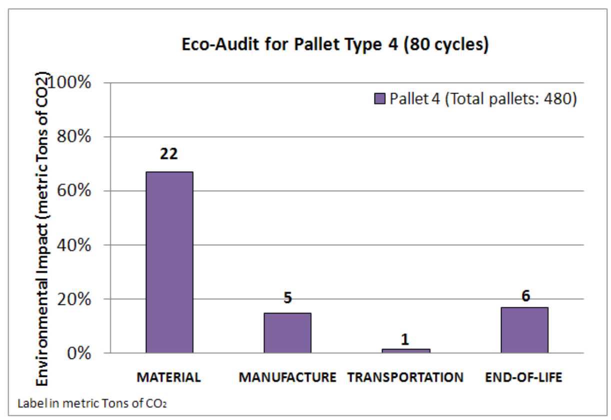
(a) Pallet type 1



(b) Pallet type 2



(c) Pallet type 3



(d) Pallet type 4

Figure 11. Eco-Audit per pallet type (80 cycles)

The environmental impact per life-cycle stage (in metric Tons of CO_2) for each pallet type is given in Figure 11. Since pallet type 1 has the highest failure fraction (1/3 per cycle), these pallets are damaged more often; consequently, more of these pallets (12,800) are needed to satisfy the demand than when using other pallet types. Furthermore, the system environmental impact is the highest when using pallets type 1, releasing a total of 270 metric Tons of CO_2. Also, for the same functional unit, a total number of 1,670 pallets are required to fulfill the demand when using pallets type 2 and type 3, creating a total

environmental impact of 41 and 40 metric Tons of CO_2. Only 480 pallets of type 4 would be required because their reuse percentage is very high compared to the other pallet types.

The eco-audits per pallet type validates that the Material life-cycle stage, for all four pallet types in the study, creates the highest CO_2 footprint among all, representing more than 70 percent of total system environmental impact. On the other hand, it is important to note that this may vary if the total miles of transportation were to increase (e.g. if 1,000 miles would be travelled instead of 300 miles). In this case, it is highly expected that the Transportation stage may represent the life-cycle stage with highest environmental impact. However, under the assumptions of the eco-audit it can be concluded that the CO_2 footprint from the Material stage is much higher than the CO_2 footprint from Manufacture and End-of-Life life-cycle stages.

<u>Validation where the objective function is minimization of monetary costs</u>

This section validates the optimization model when minimizing the total system cost measured in U.S. dollars. Because pallets are charged the same purchase/leasing cost ($C_{o_{p,(i,j)}}$) each cycle whether the pallet is new, reused, repaired, or made of recycled material, a simple economic analysis can determine which pallet is more cost effective. Pallets type 1 and 3 have the same and lowest purchase/leasing cost, although only pallet type 1 is sold after use during one cycle, which makes this pallet the cheapest among the pallets in the study and most preferable. Pallet type 2 is the most expensive among the wooden pallets, and in fact, is the only pallet that charges a cost of return. Even though pallet type 4 (plastic pallet) has a credit for returning the pallet to the pallet provider, it is an expensive pallet because of its higher leasing cost. Detailed costs applicable per pallet type are shown in Table 15.

Table 15. Pallet costs associated to each pallet management system (or pallet type)

PALLET TYPE	MATERIAL/ LOGISTICS	COSTS				
		Purchase/Leasing (Co) ($/pallet)	Transportation* (CT) (loaded pallets) ($/pallet-mile)	Transportation* (CT) (unloaded pallets) ($/pallet-mile)	Selling/Credit for Return (S) ($/pallet)	Transportation Cost of Return (CT) ($/pallet)
Pallet 1	Wood Buy/Sell	$5.00	$0.1104	$0.0055	$2.00	$0.00
Pallet 2	Wood/Leased	$5.80	$0.1104	$0.0055	$0.00	$0.07
Pallet 3	Wood/Leased	$5.00	$0.1104	$0.0055	$0.00	$0.00
Pallet 4	Plastic/Leased	$6.00	$0.1104	$0.0055	$0.25	$0.00

**Assuming TL of loaded pallets:24 pallet; TL of unloaded pallets: 480 pallets*

Note. Cost information on table was obtained through personal communication with Chris Merta, Ongweoweh Corp. July 15, 2009; Danielle Rozelle, iGPS January 13, 2010; Heather Tarbet, CHEP January 15, 2010; Mike Tebay, PECO Pallet January 28, 2010; Tim Murphy, local grocery distributor, February 3, 2010.

Different scenarios were run to validate that the model produces logically correct solutions when minimizing cost. To do so, a *costs base scenario* is used as reference for comparison for further statements.

The *cost base scenario* results are shown in Tables 16 and 17. For a time horizon of 6 months, 297,698 pallets type 1 are manufactured and represent the only pallet type used. The total system cost required to satisfy the pallet demand for this time period is $14.9 million. For a time horizon of 1 year, the total system cost increases to $32.1 million and a mix of pallets type 1 and 3 are used to satisfy the demand; pallet type 1 representing 99 percent (569,827 pallets) and pallet type 3 representing 1 percent (18,895 pallets) of total pallets manufactured. It is expected that by increasing the time period in study, pallets with a longer lifespan and less cost will be dominating the system.

Table 16 shows the need of a total of 924,298 pallet runs required to fulfill the demand for a time horizon of 6 months. From these total pallets, 297,698 are new pallets manufactured, 566,954 are reused pallets, and 25,646 are repaired pallets. In addition, for a time horizon of 1 year, pallets type 1 and type 3 are used to fulfill the demand, whether they are newly manufactured, reused, or repaired.

Table 16. Cost base scenario - Number of pallets used when minimizing system cost (Time horizon: 6 months)

Total System Cost: **14,906,058** **US dollars**
14.9 **Million US dollars**

NUMBER OF PALLETS							
Pallet Type	New (Manufactured)	Reused w/o Repair	Repaired to Reuse	Recycled to Reuse	Initial Inventory	Number of pallet runs to satisfy demand	Pallet Type %
Pallet 1	297,698	566,954	25,646	-	34,000	924,298	100%
Pallet 2	-	-	-	-	-	-	0%
Pallet 3	-	-	-	-	-	-	0%
Pallet 4	-	-	-	-	-	-	0%
	Total number of pallet runs to satisfy demand for a time horizon of 6 months:					924,298	

Table 17. Cost base scenario - Number of pallets used when minimizing system cost (Time horizon: 1 year)

Total System Cost: **32,119,278** **US dollars**
32.1 **Million US dollars**

NUMBER OF PALLETS							
Pallet Type	New (Manufactured)	Reused w/o Repair	Repaired to Reuse	Recycled to Reuse	Initial Inventory	Number of pallet runs to satisfy demand	Pallet Type %
Pallet 1	569,827	1,278,700	57,354	-	34,000	1,939,881	99%
Pallet 2	-	-	-	-	-	-	0%
Pallet 3	18,895	-	159	-	-	19,054	1%
Pallet 4	-	-	-	-	-	-	0%
	Total number of pallet runs to satisfy demand for a time horizon of 1 year:					1,958,935	

The following hypotheses were used to validate the cost optimization model.

- *Statement 1: How much does the price of type 1 pallets affect the pallet management system to be chosen when minimizing the system cost?*

  Part A - without modifying pallet type 1 selling price ($S_{1,(i,j)}$= $2)

  Part B - assuming pallet type 1 does not get sold after use but is only returned ($S_{1,(i,j)}$= 0)

Predicted behavior: If the pallet type 1 purchase cost is more expensive than the other pallet types in the study, then a different type (other than pallet type 1) would be chosen.

Model results: The model was run by changing the pallet type I purchase cost ($C_{o_{1,(i,j)}}$) to different values, such as 4, 5, 6, 7, 9, and 12 dollars per pallet. For Part A, pallets of type I are manufactured when their purchase cost is low (less than $6/pallet), as shown in Figure 12. However, pallets of type 3 are manufactured when their cost equals the cost of pallets type I, and are the only type of pallet manufactured when pallet type I purchase cost is $9 per pallet or higher. Furthermore, under scenario Part B (Figure 13), the trend of pallets use is similar, although the change of preferred pallet type from type I to type 3 occurs sooner, since the pallets type I selling price ($S_{1,(i,j)}$) is zero.

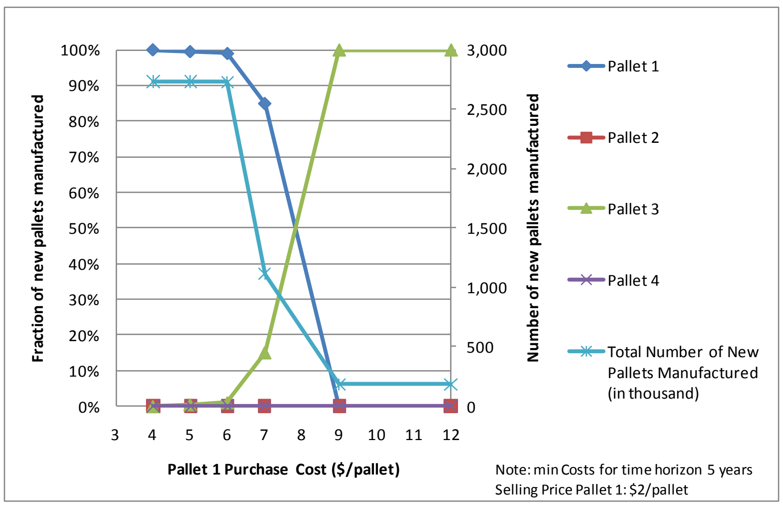


Figure 12. Statement 1 - Part A – Percentage of new pallets manufactured for different pallet type 1 purchase costs and for pallet type 1 selling price = $2/pallet (Time horizon: 5 years)

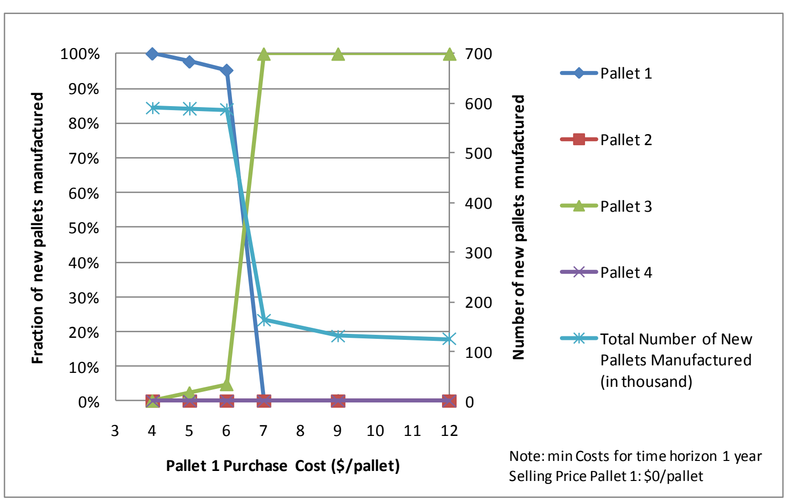


Figure 13. Statement 1 - Part B - Percentage of new pallets manufactured for different pallet type 1 purchase costs and for pallet type 1 selling price = $0/pallet (Time horizon: 1 year)

- *Statement 2: How much does pallet type 4 leasing cost affect the pallet management system to be used when minimizing cost?*

Predicted behavior: If pallet type 4 leasing cost ($C_{o_{4,(i,j)}}$) is changed in the way that its net cost (difference between the purchase/leasing cost and the selling price/credit for return) is the lowest among all pallet types in study, then this pallet type is expected to be chosen.

Model results: When pallet type 4 has a leasing cost of $4 per pallet, it is the only type manufactured, as shown in Figure 14.

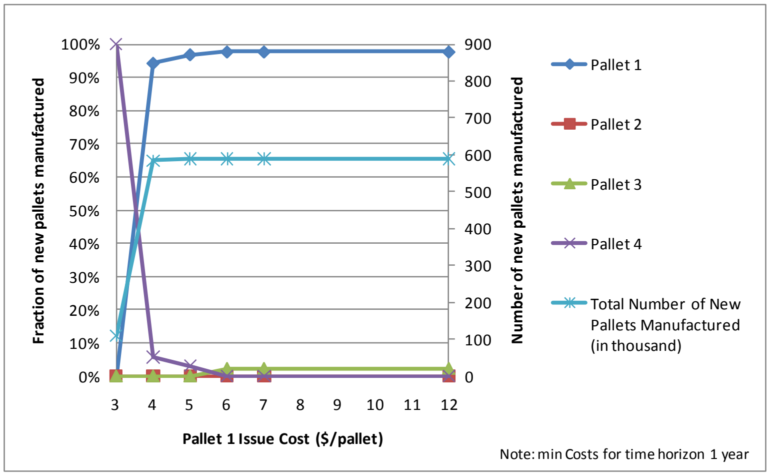


Figure 14. Statement 2 – Percentage of new pallets manufactured for different pallet type 4 leasing costs (Time horizon: 1 year)

- *Statement 3: Which mix of pallet types will make the system perform under the lowest costs when all four pallet types have the same purchase/leasing cost ($C_{o_{p,(i,j)}}$= $5)?*

Predicted behavior: Pallet type 1 is expected to be the preferred pallet since a credit is obtained when selling these pallets.

Model results: Since pallets type 1 are sold after used, this pallet type is preferred for 96 percent of total new pallets manufactured as expected, while pallets type 2, 3, and 4 represent 0.6, 0.4, and 3 percent,

respectively, as shown in Figure 15. Pallet type 4 is the second preferred pallet because it has a credit for return and has the longest lifespan.

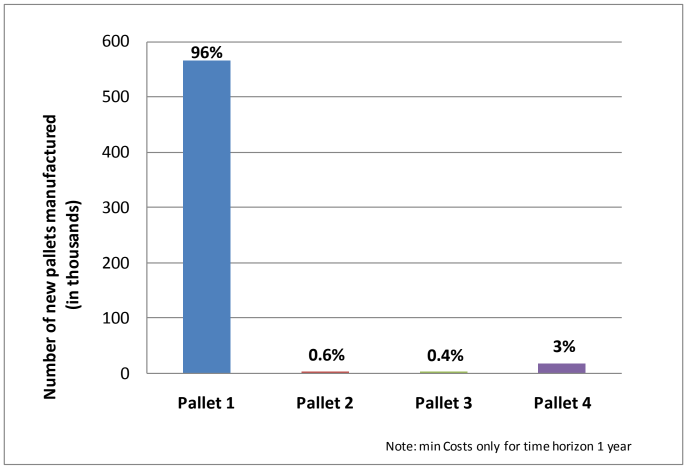


Figure 15. Statement 3 – New pallets manufactured when all 4 pallet types have the same purchase/leasing cost ($5/pallet)

- *Statement 4: Would plastic pallets (type 4) be chosen if the wood supply decreases, assuming this generates an issue cost increase ($C_{o_{p,(i,j)}}$) of 30 percent for wooden pallets (type 1, 2, and 3)?*

Predicted behavior: Pallets type 4 may be manufactured since, in the proposed statement, this pallet type may cost less than a wooden pallet. Moreover, pallet type 1 would cost $6.5 per pallet instead of $5/pallet, pallet type 2 would cost $7.5 per pallet instead of $5.8/pallet, and pallet type 3 would cost $6.5 per pallet instead of $5/pallet, compared to the cost of a plastic pallet which is $6/pallet. However, under this scenario pallets type 1 are still more cost effective because they are sold for $2 per pallet.

Model results: Under this assumption plastic pallets would be manufactured but in very low quantity, representing 15,655 from a total of 297,713 pallets for a time horizon of 6 months, and 26,859 from a total of 586,818 pallets for a time horizon of 1 year, as shown in Table 18. Pallets type 1 are still cheaper and represent the highest percentage of total new pallets manufactured.

Table 18. Statement 4 – Pallets types manufactured when wooden pallet issue costs increases

Time Horizon		6 months	1 year
Total System Cost (million $)		16	35
Number of New Pallets Manufactured	Pallet 1	282,042	559,959
	Pallet 2	-	-
	Pallet 3	-	-
	Pallet 4	15,655	26,859

Overall, the optimization model chooses a logical mix of pallet management systems depending on the values given to the different parameters/factors and the objective considered. Furthermore, pallets type 2 are never chosen, neither when minimizing the environmental impacts of the system, nor when minimizing the total system cost; therefore, this pallet type will not be taken into account for future experiments analysis.

CHAPTER V

CASE STUDY - RESULTS AND ANALYSIS

A case study from a large grocery distributor/retailer in the Northeast is presented. The results and analysis section describes and interprets different outputs obtained when running the algorithm for the mixed integer optimization model under various scenarios. These scenarios can include change of factors, parameters, and/or pallet characteristics to see their impact on the pallet management systems chosen.

5.1 CASE STUDY GROCERY DISTRIBUTOR/RETAILER

The product distributor/retailer analyzed in this case study owns multiple distribution centers (8), multiple retailers (75), and a single return center, as shown in Figure 16. The case study considers pallets type 1, 3, and 4 defined in the validation section. Pallet type 1 represents a wooden pallet under a buy/sell program. Pallet types 3 and 4 are leased pools. Pallet type 3 is a wooden pallet, while pallet type 4 is a plastic pallet.

All stated assumptions included in the modeling approach and validation section apply. Monetary costs involved per pallet type are the costs presented earlier in Table 15 (Chapter III). In addition, the carbon dioxide footprint from each life-cycle stage per pallet type is detailed in Appendix A.

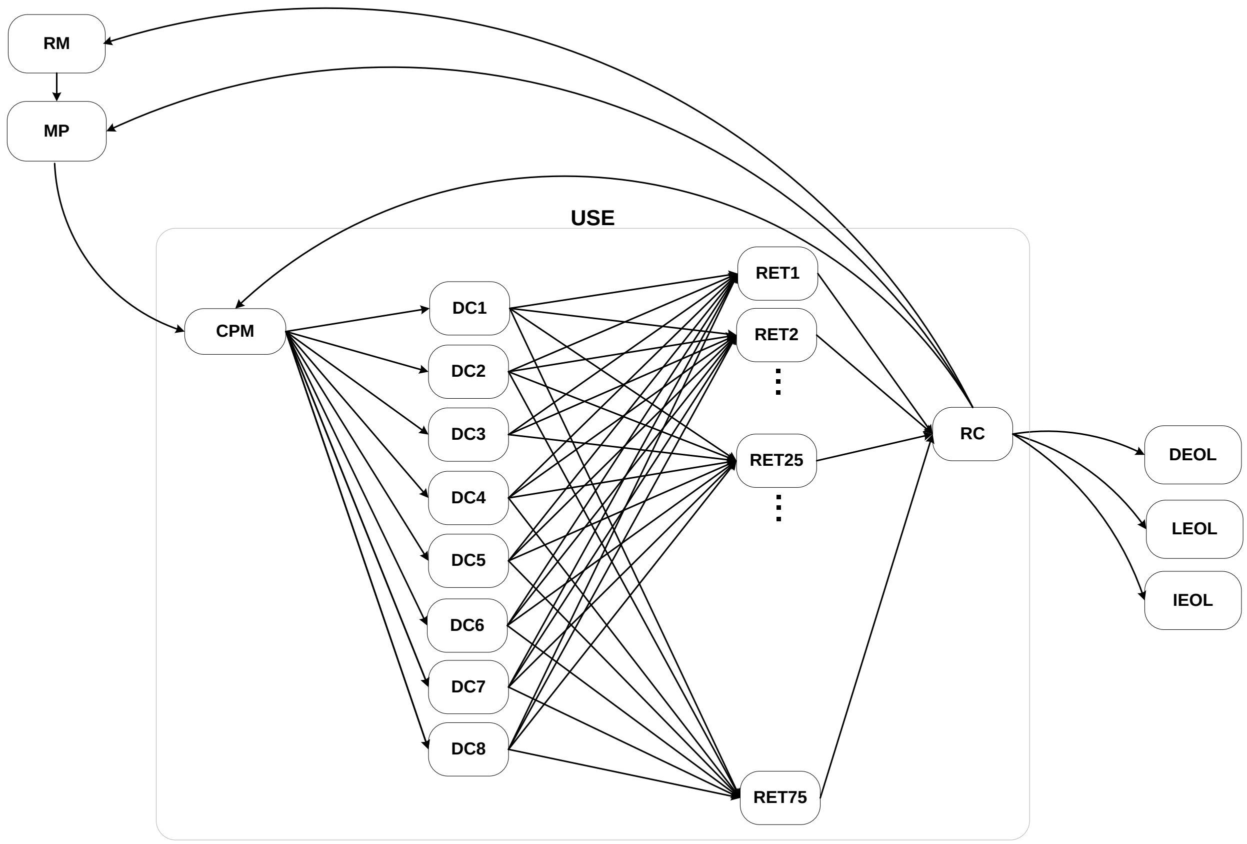


Figure 16. Pallets life-cycle network applied to the case study

Because the case study is based on a grocery distributor/retailer a pallet demand exists at two different locations: distribution centers and retailers. Each of the distributor facilities has a different demand. Data on pallet demand at each of the 8 DCs and each of the 75 retailers is known for 5 weeks. For the purpose of the study, this data is repeated when analyzing time horizons longer than 5 weeks. Tables 19 and 20 show the weekly demand at the distribution centers and retailers, respectively. For detailed information on pallet demand per facility refer to Appendix A. In addition, transportation miles within distribution centers, retailers, and the return center are specified in Appendix A.

Table 19. Weekly pallet demand at distribution centers (Dc)

Dc: Pallet Demand at Distribution Centers	Time Period (week)				
	1	2	3	4	5
Sum of total pallet demand	33,582	36,540	37,497	35,938	36,763

Table 20. Weekly pallet demand at retailers (Db)

Db: Pallet Demand at Retailers	Time Period (week)				
	1	2	3	4	5
Sum of total pallet demand	33,682	35,905	31,182	31,089	32,541

Table 21 shows the percentages of damaged pallets disposed to the different end-of-life scenarios.

Table 21. Pallets end-of-life percentages per pallet type

Pallet End-of-Life Scenario	Pallet Management System		
	1	3	4
Repair	10%	80%	0%
Recycle	0%	0%	100%
Downcycle	89%	19%	0%
Landfill	1%	1%	0%
Incineration	0%	0%	0%

5.1.1 MODELING PALLET LIFESPAN

The literature review found that different pallet companies have conducted LCA analyses in the past years (CHEP, 2008; iGPS, 2008), and different assumptions regarding pallet lifespan (based on number of trips[6] a pallet may last before damaged) were used in each of the studies.

For the purpose of this work, the pallet failure was calculated by averaging (from both sources) the number of cycles a pallet lasts before damaged (for whitewood, pooled wood and pooled plastic pallets). Estimations of pallet failure fractions are detailed per pallet type.

[6] Note: the word trip in pallet providers' context is referred as cycle for the research purpose.

Whitewood Pallet:

CHEP states that whitewood pallets last 4 cycles (Brindley, 2010) (20 trips in the present study, since there are 5 trips per cycle) and iGPS states that whitewood last 2 cycles (iGPS, 2008) (10 trips for the study). On average whitewood pallets last 15 trips (3 cycles) before damaged, which translates into a failure fraction of 1/3 per cycle. In other words, 33.24 percent of total pallets shipped every cycle leave the system. Considering the trips and handlings per trip, 1/9 of the pallets arrived at the DC and 2/9 of the pallets arrived at the RC present failure.

Pooled Wooden Pallet:

CHEP states that whitewood pallets last 30 cycles (Brindley, 2010) (150 trips in the present study) and iGPS states that they last 15 cycles (iGPS, 2008) (75 trips for the study). On average pooled wooden pallets last 115 trips (23 cycles) before damaged, which translates into a failure fraction of 1/23 per cycle. Further, 4.35 percent of total pallets shipped every cycle get damaged or present failure. Therefore, 1/69 and 2/69 of pallets arrived at DC and RC, respectively, leave the system.

Pooled Plastic Pallet:

CHEP states that plastic pallets last 60 cycles (Brindley, 2010) (300 trips in the present study) and iGPS states that they last100 cycles (iGPS, 2008) (500 trips for the study). On average pooled plastic pallets last 400 trips (80 cycles), which translates into a failure fraction of 1/80 per cycle. Further, 1.25 percent of total pallets shipped every cycle get damaged. Moreover, 1/240 and 2/240 of pallets arriving the DC and RC, respectively, present failure.

The lifespan of a pallet may depend on different factors, e.g. pallet material (i.e. softwood, hardwood, plastic, metal), durability, structure (block vs. stringer), etc. Since pooled wooden pallets are designed to be reused many times, they typically last longer than whitewood pallets. Figure 17 represents the percentage of damaged pallets estimated per cycle.

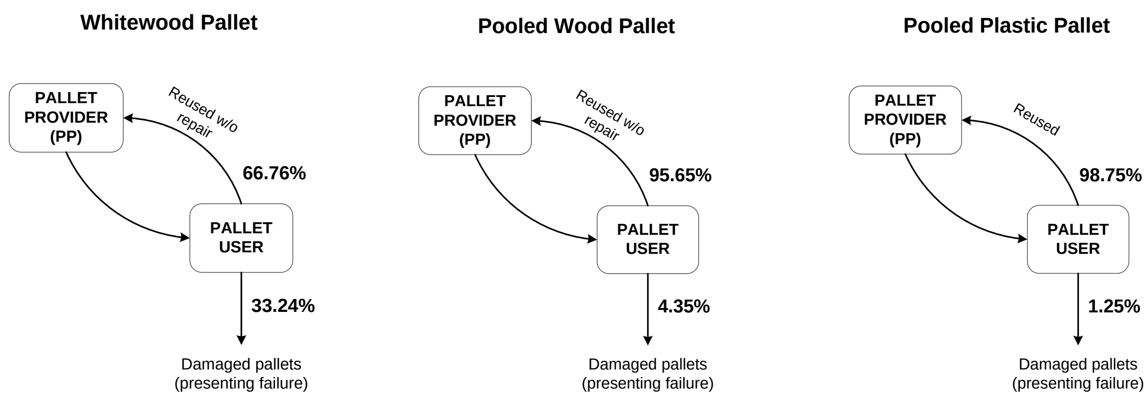


Figure 17. Physical failure fraction representation per pallet

5.2 Results and Analysis

The questions wished to answer are:

- *Question 1:* What is the tradeoff between environmental impacts and costs?
- *Question 2:* Which mix of pallet management systems minimizes the environmental impacts and costs under different time frames?
- *Question 3:* How much do pallet weight and purchase/leasing cost affect the pallet management system used? How much does this affect the system costs and its environmental burden?
- *Question 4*: How much do pallet weight and the CO_2 footprint from material production affect the pallet management system used? How much does this affect the system costs and its environmental burden?
- *Question 5:* Does demand affect the preferred pallet management system?
- *Question 6:* Does transportation affect the preferred pallet management system?
- *Question 7:* How can new regulations on pallet end-of-life scenarios influence the system carbon footprint?

5.2.1 What is the Tradeoff between Environmental Impacts and Costs?

The tradeoff between the total environmental impacts of the system and its costs is represented in Figure 18. This figure illustrates the environmental and cost values for a time horizon of 1 year, although the trend remains similar when studying different time frames. From the graph, it can be understood that if spending 10.6 percent more on pallets than the minimum required ($35,520,957 instead of $32,119,278; $3.4 millions more) the system would perform under the lowest environmental impacts, releasing 4.68 metric KTons of CO_2 compared to 14.1 metric KTons of CO_2.

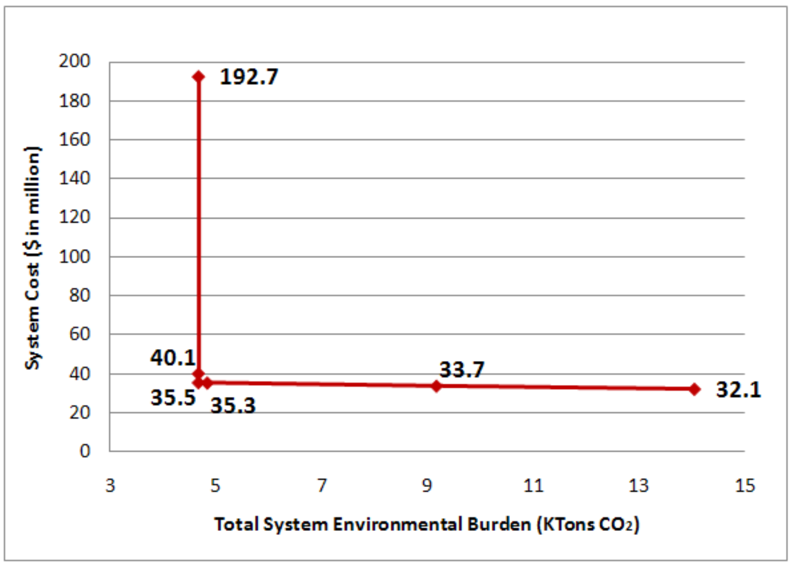
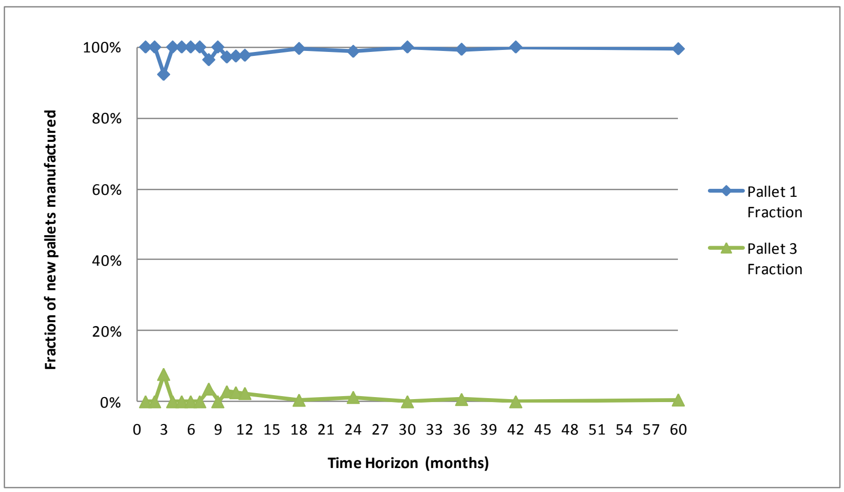


Figure 18. Tradeoff between system environmental impacts and costs (Time horizon: 1 year)

Furthermore, if the same analysis is performed for a time horizon of 6 months (refer to Appendix D), an additional 9.82 percent of the minimum total system costs ($14,906,058) would need to be spent (a difference of approximately $1.5 million) to reduce the system carbon footprint to the lowest possible value. The system, when performing under the lowest environmental impact, releases 3.46 metric KTons of CO_2.

5.2.2 WHICH MIX OF PALLET MANAGEMENT SYSTEMS MINIMIZES THE ENVIRONMENTAL IMPACTS AND COST UNDER DIFFERENT TIME FRAMES?

This analysis addresses what mix of pallet types would be manufactured (introduced) in the system in order to satisfy pallet demand while minimizing the total environmental impacts subject to minimum cost. The algorithm in Chapter II was run for the different time horizons illustrated in Figure 19. Results show that pallets type 1 represent more than 90 percent of total new pallets manufactured, pallets type 3 represent the fraction remaining, and pallets type 4 are not used under this scenario.



Note. Pallet fraction represents the total number of pallets manufactured new for the entire time horizon.

Figure 19. Pallet use per pallet type when minimizing environmental impacts subject to minimum cost

Even though the purchase cost of pallet type 1 is the same as the leasing cost of pallet type 3 ($5/pallet), pallets type 1 are sold after use (for $2/pallet), making this pallet type the less expensive. As a result, these pallets (type 1) are preferred when optimizing the system under this scenario.

When analyzing the total number of new pallets manufactured for each time horizon, it can be noted that after a time horizon of 8 months the number of pallets type 3 remains almost constant (approximately 13,600 pallets), whereas the number of pallets type 1 increases for longer time horizons, representing approximately 370,000 pallets for a time horizon of 8 months and 2,700,000 when running

the model for 5 years (refer to Appendix D for detailed graph). This is because the model, under longer time horizons, chooses to manufacture a pallet type with a longer lifespan, such as pallet type 3. Moreover, pallets type 1 still optimize the system since they are the less expensive pallet with the least weight (45 lbs/pallet), thus the lowest total material CO_2 footprint.

Figure 20 represents the percentage of new pallets manufactured per pallet type that optimize the system when minimizing the total environmental impacts but constrained by 125 percent of the minimum system cost (α=25 percent). Under this scenario, only pallet type 3 is manufactured.

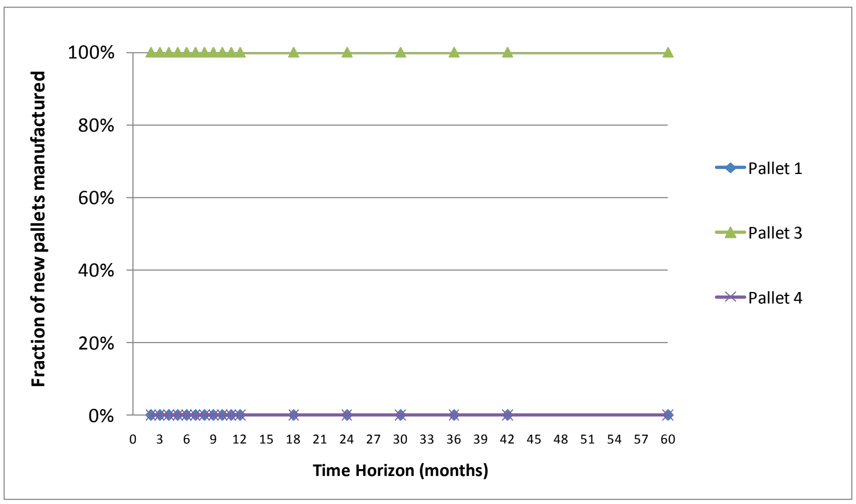


Figure 20. Pallet use per pallet type when minimizing system environmental impacts allowing costs to increase by 25 percent the minimum cost

When only pallets of type 3 are used, a smaller number of pallets are needed to satisfy the pallet demand. For example, for the scenario where the system performs under the lowest system cost, approximately 300,000 of pallets type 1 are needed to satisfy the pallet demand for 6 months; while in the scenario where 25 percent above the minimum costs is allowed, only 105,000 pallets type 3 are needed. Furthermore, for time horizons of 2 years under the first scenario (minimum costs), a total of 1,123,601 pallets are manufactured, from which 1,109,940 are pallets type 1 and the rest pallets type 3. Under the second scenario (relaxing the system cost allowing 25 percent above the minimum) a total of

125,732 pallets are manufactured, all represented by pallets type 3. This result is expected, since for a time horizon of 2 years (104 weeks), approximately 8 times more pallets type 1 are needed than pallets type 3 because of their different lifespan characteristic. Pallet type 1 lasts approximately 3 cycles before getting damaged, while pallet type 3 lasts 23 cycles before damaged.

5.2.3 HOW MUCH DO PALLET WEIGHT AND PURCHASE/LEASING COST AFFECT THE PALLET MANAGEMENT SYSTEM USED? HOW MUCH DOES THIS AFFECT THE SYSTEM COSTS AND ITS ENVIRONMENTAL IMPACTS?

From the validation section and previous experiments it is known that factors such as pallet weight and pallet purchase/leasing cost may have a significant impact on the output of the model.

The experiment was performed for pallet weight ($W_{p,m,(i,j)}$) and pallet purchase/leasing cost ($C_{o_{p,(i,j)}}$), at two levels for each pallet management system (high and low), first minimizing the total system cost and then minimizing environmental impacts subject to these minimum cost. Figure 21 shows the values for each level given to each of the pallet types.

The design for two factors and at two levels for each of the three pallet types, results in an experimental design of 64 different combinations (also referred as runs or scenarios) (refer to Appendix D for detailed 64 combinations). This design was run for two different time horizons: 6 months and 2 years.

	FACTORS	PALLET 1		PALLET 3		PALLET 4	
		low	high	low	high	low	high
A	Weight (lbs/pallet)	40	65	45	75	40	65
B	Purchase/Leasing Cost ($/pallet)	$3	$9	$4	$7	$5	$7

Source: different pallet websites and personal communications referenced in validation section

Figure 21. Levels for weight and purchase/leasing cost factors included in analysis

The same proportion of pallet management systems was obtained for a time horizon of 6 months and 2 years. In 50 percent of the cases where pallet of type 1 weight is at a low level (40 lbs/pallet) (16 of 64 combinations), these pallet types are the only type manufactured; whereas, in 25 percent of the cases pallets of type 3 are chosen, and in the remaining cases pallets type 4 are manufactured. A similar situation occurs when pallet type 1 is at a high weight (65 lbs/pallet).

In 100 percent of the cases where pallets of type1 are at a low purchase cost ($3/pallet) (32 of total 64) these pallet types represent all the pallets manufactured. Otherwise, these are never manufactured when they are at a high purchase cost ($9/pallet). Pallets of type 3 are manufactured when its leasing cost is at low ($4/pallet) while pallet type 1 purchase cost is at a high level. Pallets of type 4 are manufactured when both pallets type 1 and type 3 purchase/leasing costs are at high levels, regardless at what leasing cost they pallets type 4 are (refer to Appendix D for detailed results).

A conclusion drawn from this analysis is that pallet weight under the factor levels studied does not affect the output of the model. Furthermore, the pallets purchase/leasing cost drives which pallet is manufactured. The pallet type chosen when minimizing the environmental impacts subject to minimum cost will be the pallet type with the lowest purchase/leasing cost.

Results may vary when the total system cost does not perform at its lowest level but at some percentage higher, or when the objective functions are reversed. Therefore, other tests were run to analyze these possible effects. Moreover, from the 64 combinations, 3 scenarios were chosen to be analyzed and compared within each other when performing under different scenarios, as shown in Table 22. They were chosen because of their different pallet outputs; a different pallet type was chosen to be manufactured 100 percent of the time in each of the three cases, where in Run 1 pallets type 1 were chosen, in Run 2 pallets type 3 were chosen, and in Run 3 pallets type 4 were chosen. Table 23 shows the results for a time horizon of 2 years, including total system cost, total system environmental impact, and type and quantity of pallets manufactured.

Table 22. 3 scenarios from total 64 combinations

	Weight			Purchase/Leasing Cost		
Runs	**P1**	**P3**	**P4**	**P1**	**P3**	**P4**
1	low	low	low	low	low	low
2	low	low	low	high	low	low
3	low	low	low	high	high	low

=

	Weight			Purchase/Leasing Cost		
Runs	**P1**	**P3**	**P4**	**P1**	**P3**	**P4**
1	40	45	40	3	4	5
2	40	45	40	9	4	5
3	40	45	40	9	7	5

Table 23. Minimizing environmental impacts subject to minimum system cost (Time horizon: 2 years)

Rate of Cost Increase	Run	System Cost (in million)	System Env. Cost (KTons CO_2)	New Pallets Manufactured						Total New Pallets Manufactured
				Pallet 1		Pallet 3		Pallet 4		
α = 0	**1**	**$ 56.27**	**24.6**	1,125,070	100%	-	0%	-	0%	**1,125,070**
α = 0	**2**	**$ 67.70**	**5.6**	-	0%	137,963	100%	-	0%	**137,963**
α = 0	**3**	**$ 70.56**	**9.4**	-	0%	-	0%	109,225	100%	**109,225**

When using pallet type 1 instead of pallet type 4, a total of $14.29 million is saved, although the system releases 15.2 metric KTons more of CO_2. On the other hand, when the system chooses pallets type 3 instead of pallets type 4, the system saves $2.86 million and decreases its CO_2 footprint by 3.8 metric KTons.

The model was also run under the scenario where costs can increase to 20 percent the minimum cost (α=20 percent). For each of the three runs, pallets type 3 were chosen, as shown in Table 24.

Table 24. Minimizing environmental impacts when cost can increase to 20 percent the minimum cost (Time horizon: 2 years)

Rate of Cost Increase	Run	System Cost (in million)	System Env. Cost (KTons CO_2)	Env. Impact Decrease	New Pallets Manufactured						Total New Pallets Manufactured
					Pallet 1		Pallet 3		Pallet 4		
α = 20%	**1**	**$ 67.24**	**5.4**	**78%**	-	0%	125,734	100%	-	0%	**125,734**
α = 20%	**2**	**$ 68.05**	**5.4**	**3%**	-	0%	125,734	100%	-	0%	**125,734**
α = 20%	**3**	**$ 79.21**	**5.4**	**42%**	-	0%	125,734	100%	-	0%	**125,734**

Pallets type 3 have a higher overall cost than pallets type 1 since no credit is obtained from returning pallets type 3 to the providers, although these pallets last longer than pallets type 1 and have less CO_2

footprint from material production than pallets type 4. The total system carbon footprint gets reduced in each of the scenarios analyzed, as shown in Table 24, and by comparing to the scenarios in Table 23. For example, in Run 1 by increasing 19.5 percent of the minimum in pallet expenditures ($10.96 million more), the CO_2 footprint from the entire system is reduced by 78 percent (19.2 metric KTons of CO_2 emissions).

Table 25 shows the results when the total system cost is minimized subject to the minimum system environmental cost. The total system CO_2 footprint results in 5.4 metric KTons of CO_2, which equals what was obtained when minimizing the total environmental impacts while the minimum cost was allowed to be increased by 20 percent.

Table 25. Minimizing system cost subject to minimum environmental impacts (Time horizon: 2 years)

Rate of Cost Increase	Run	System Cost (in million)	System Env. Cost (KTons CO2)	New Pallets Manufactured						Total New Pallets Manufactured
				Pallet 1		Pallet 3		Pallet 4		
α = 0	1	$ 67.24	5.4	-	0%	125,734	100%	-	0%	125,734
α = 0	2	$ 68.05	5.4	-	0%	125,734	100%	-	0%	125,734
α = 0	3	$ 79.21	5.4	-	0%	125,734	100%	-	0%	125,734

Likewise, the optimization model was run to minimize the total system cost while allowing the system to release 20 percent more than the minimum carbon dioxide, as shown in Table 26.

Table 26. Minimizing system cost when environmental impacts can increase to 20 percent the minimum environmental impact (Time horizon: 2 years)

Rate of Cost Increase	Run	System Cost (in million)	Maximum System Env. Cost Allowed (KTons CO2)	New Pallets Manufactured						Total New Pallets Manufactured
				Pallet 1		Pallet 3		Pallet 4		
α = 20%	1	$ 66.08	6.5	69,601	38%	113,585	62%	-	0%	183,186
α = 20%	2	$ 67.70	6.5	-	0%	138,239	100%	-	0%	138,239
α = 20%	3	$ 76.28	6.5	-	0%	88,603	74%	31,920	26%	120,523

As concluded earlier, the results are driven by the costs of the pallets. Therefore, the cheapest pallet will be the predominant in the system. In Run 1, pallets type 3 are manufactured during the first weeks of the time horizon because of their long lifespan and pallets type 1 are chosen because their low purchase cost. In Run 2, only pallets type 3 are chosen as preferred because pallets type 1 are too costly and pallets type 4 have the highest carbon footprint from material production.

5.2.4 How much do pallet Weight and the CO_2 footprint from Material primary production affect the Pallet Management System used? How much does this affect the system costs and its environmental burden?

From the previous analysis it was noted that when minimizing the system environmental impacts subject to the minimum cost, the output of the model was driven by the costs of the pallets. Moreover, the pallets manufactured in order to satisfy the pallet demand were usually the less expensive pallets. As a result, this section studies when minimizing the system cost subject to environmental impacts, thus giving priority to the system carbon footprint. In addition, similar costs were given to the pallet types, as shown in Table 27.

Table 27. Costs modified per pallet type for this analysis

COST PER PALLET TYPE	Pallet Type		
	PALLET 1	PALLET 3	PALLET 4
Purchase/Leasing Cost	$ 6.25	$ 5.00	$ 5.50
Selling Price/Credit for Return	$ 1.50	$ -	$ 0.25
Total net Cost per pallet	**$ 4.75**	**$ 5.00**	**$ 5.25**

The factors considered under this analysis are pallet weight ($W_{p,m,(i,j)}$) and the CO_2 footprint from material primary production ($M_{p,m,(i,j)}$). An experiment was developed for these two factors, at three levels only for pallet type 4, with a total of 9 different combinations. The design was run for two

different time horizons: 6 months and 2 years. Figure 22 shows the values for each level given to each of the pallet types. Refer to Appendix D for details of the 9 combinations.

	FACTORS	PALLET 1		PALLET 3		PALLET 4					
						low		med		high	
A	Weight (lbs/pallet)	45		65		20		35		47.5	
B	CO_2 Footprint, primary material production ($lbsCO_2/lb$)	Hardwook: oak, across grain	0.4495	Softwood: pine, across grain	0.4495	Recycled: Plastic & Steel	0.863 0.695	Only virgin Plastic	2.05	Plastic Steel (virgin)	2.05 2.485

Source: Cambridge Engineering Selector software tool (CES, 2010)

Figure 22. Levels of factors weight and material CO_2 footprint per pallet type included in analysis

Following are the factor levels explained in detail:

- Wooden pallet type 1 is assumed to weigh 45 pounds, an average weight for this type of pallets made of hardwood oak;
- Pallet type 3 is assumed to be a softwood pine pallet with a weight of 65 pounds per pallet (average weight for wooden pooled pallets);
- Plastic pallet type 4 is analyzed under different scenarios by giving different material alternatives: *(i)* pallet made of recycled plastic and recycled steel for reinforcement bars; *(ii)* pallet made of only virgin plastic, and *(iii)* pallet made of virgin plastic and raw steel. Each of these material alternatives are also being analyzed with different weights, such as 20, 35, and 47.5 pounds per pallet.

Results when minimizing total costs subject to minimum environmental impacts for a time horizon of 2 years are shown in Table 28. As noted in the results of the model, in all scenarios where pallet type 4 weighs 20 pounds, this pallet type is manufactured in more than 95 percent. When pallet type 4 is made of all recycled material and weighs 35 pounds per pallet they are still preferred, representing 90 percent of total new pallets manufactured. The higher the weight and material CO_2 footprint of pallet type 4, the

less these pallets are manufactured. Consequently, wooden pallets type 3 are preferred when plastic pallets weigh 35 pounds per pallet or more and when they are made of raw material or only plastic. Pallet type 1, even being the less expensive pallet, does not get manufactured in any amount because of its short lifespan and high weight.

Table 28. Results when minimizing system cost subject to minimum environmental impacts (Time horizon: 2 years)

Rate of Cost Increase	Scenario or Run	System Cost (in million)	Total Environmental Impact (KTons CO_2)	New Pallets Manufactured						Total Pallets
				Pallet 1		Pallet 3		Pallet 4		
α=0	1	$ 72.49	3.7	-	0%	-	0%	108,398	100%	108,398
α=0	2	$ 72.37	4.9	-	0%	1,734	2%	101,852	98%	103,586
α=0	3	$ 72.35	4.9	-	0%	4,506	4%	99,362	96%	103,868
α=0	4	$ 72.37	6.0	-	0%	1,130	1%	102,411	99%	103,541
α=0	5	$ 71.70	7.0	-	0%	94,797	79%	24,794	21%	119,591
α=0	6	$ 71.67	7.1	-	0%	98,374	82%	21,916	18%	120,290
α=0	7	$ 71.48	7.2	-	0%	125,732	100%	-	0%	125,732
α=0	8	$ 71.48	7.2	-	0%	125,732	100%	-	0%	125,732
α=0	9	$ 71.48	7.2	-	0%	125,732	100%	-	0%	125,732

Different outcomes are obtained in Run 1 relative to Run 7 (as shown in Table 28), where in both cases plastic pallets are made of all recycled material but have different weights. In Run 1, pallet type 4 weighs only 20 pounds and is the only type chosen creating 3.7 metric KTons of CO_2. However, the pallet chosen in Run 7 is type 3. Accordingly, in Run 1 the total system environmental impact is almost half the impact of Run 7. As a result, plastic pallets with low weight (20 lbs/pallet) and made of recycled material (plastic and steel) are the pallets chosen to perform in a sustainable environment.

In the scenario where the system is minimized for total system cost when the environmental impacts can increase up to 5 percent (Table 29), pallets type 1 are manufactured in certain percentages under different scenarios (mainly when plastic pallets have high weight). Similar behavior is noted when the model runs for a time horizon of 6 months (Appendix D).

Table 29. Results when minimizing system cost allowing environmental impacts to increase by 5 percent (α=5%) (Time horizon: 2 years)

Rate of Cost Increase	Scenario or Run	System Cost (in million)	Total Environmental Impact (KTons CO_2)	New Pallets Manufactured						Total Pallets
				Pallet 1		Pallet 3		Pallet 4		
α = 5%	1	$ 8.55	3.9	-	0%	13,208	12%	93,068	88%	**106,276**
α = 5%	2	$ 11.24	5.1	-	0%	48,766	44%	63,119	56%	**111,885**
α = 5%	3	$ 11.42	5.2	-	0%	52,034	46%	60,470	54%	**112,504**
α = 5%	4	$ 13.81	6.3	-	0%	70,616	61%	45,610	39%	**116,226**
α = 5%	5	$ 16.22	7.4	5,843	4%	128,957	96%	-	0%	**134,800**
α = 5%	6	$ 16.29	7.4	7,517	6%	128,908	94%	-	0%	**136,425**
α = 5%	7	$ 16.57	7.5	14,017	10%	128,720	90%	-	0%	**142,737**
α = 5%	8	$ 16.57	7.5	14,017	10%	128,720	90%	-	0%	**142,737**
α = 5%	9	$ 16.57	7.5	14,017	10%	128,720	90%	-	0%	**142,737**

The results of the experiments when the system performs under the lowest environmental impacts show similarities with studies conducted by The Netherlands Packaging and Pallet Industry Association for CHEP. Here, the life-cycle assessment (LCA) tool was used to compare the environmental aspects for wood pallets and plastic pallets (50 percent recycled plastic and 50 percent new HDPE), considering multiple trips for both. The results of the analysis show that wood pallets are more environmentally friendly than plastic pallets, specifically because the environmental impact of the material and manufacture phases for plastic pallets is much higher. As concluded from the study, multi-use wood pallets utilize considerably less raw material and energy, and contribute far less emissions into water and air than plastic pallets (CHEP, 2008; Hamner & White, 2007). In addition, the research prepared for this thesis shows that the CO_2 footprint from plastic production is 4.56 times higher than the CO_2 footprint from wood primary production, which ensures that a wooden pallet compared to a plastic pallet with the same weight will require less energy for material production, and thus create less emissions.

A different LCA was also conducted by the association to evaluate single-use wood pallets (buy/sell) versus multi-use wood pallets (leased pools), per handling cycle. The results from this study show that the energy consumption, solid waste, and gas emissions from manufacturing and using multi-use wood pallets is approximately half that of single-use wood pallets, even though multi-use pallets cost more up front and use over twice as much wood (CHEP, 2008; Hamner & White, 2007). Furthermore, when the

optimization model proposed in this research performs under the lowest system environmental impact, the system does not choose single-use wooden pallets (similar to type 1), because of their high failure fraction and high environmental impact (measured in CO_2 emissions). Instead, it chooses pallet type 3, a pooled wooden pallet (or multi-use pallet) because of its high reuse rate, creating lower emissions (refer to Figure 20 and Table 28), which correlates to results from the LCA.

Furthermore, Franklin Associates, a leading consultant group specializing in life-cycle inventory analysis and solid waste management, conducted a LCA for CHEP in 2009. The study covered whitewood pallets, pooled plastic, and pooled wooden pallets. According to CHEP's 2009 study, the CHEP pallet generates 48 percent less solid waste, consumes 23 percent less total energy, and generates 14 percent less GHGs than pooled plastic pallets. Compared with limited use white wood pallets, the CHEP system generates 50 percent less solid waste, consumes 19 percent less total energy, and generates 5 percent less GHGs (Chaille Brindley, 2010).

5.2.5 DOES DEMAND AFFECT THE PREFERRED PALLET MANAGEMENT SYSTEM?

This section analyzes the system under different pallet demand, in order to determine if the demand factor may affect the pallet management system chosen. In this case, two pallet demands ($Dc_{i,t}$) are considered as low and high demand, where the former is 25,250 pallets and the latter is 721,280 pallets per week at the distribution centers, as shown in Figure 23.

FACTOR	PALLET 1/3/4	
	low	high
Weekly Pallet Demand (at DCs) (average number of pallets)	25,250	721,280
Weekly Pallet Demand (at RETs) (average number of pallets)	23,016	657,600

Figure 23. Levels for factor demand

First, results are analyzed for a low demand during a time horizon of 6 months when pallet costs characteristics are at their nominal values (pallet type 1 purchase cost ($C_{o_{1,(i,j)}}$) at \$5/pallet and selling price ($S_{1,(i,j)}$) \$2/pallet, type 2 leasing cost ($C_{o_{2,(i,j)}}$) at \$5/pallet, and type 4 leasing cost ($C_{o_{4,(i,j)}}$) \$6/pallet and credit for return ($S_{4,(i,j)}$) at \$0.25/pallet). In the scenario where the system cost is minimized subject to the minimum environmental impact, pallet type 3 is the pallet type chosen representing 100 percent of total new pallets manufactured. In the scenario where the system is minimized for total environmental impacts subject to minimum cost, only pallet type 1 is manufactured (Table 30). Similar outputs were obtained when considering a high pallet demand (Table 31).

Table 30. Low demand - Costs per pallet type under nominal values

	System Cost (in million)	Total Environmental Impact (KTons CO_2)	New Pallets Manufactured						Total New Pallets Manufactured
			Pallet 1		Pallet 3		Pallet 4		
min COSTS subject to min Env Costs	**\$ 12.57**	**2.5**	-	0%	70,760	100%	-	0%	**70,760**
min ENV costs subject to min Costs	**\$ 11.46**	**5.4**	224,311	100%	-	0%	-	0%	**224,311**

Table 31. High demand - Costs per pallet type under nominal values

	System Cost (in million)	Total Environmental Impact (KTons CO_2)	New Pallets Manufactured						Total New Pallets Manufactured
			Pallet 1		Pallet 3		Pallet 4		
min COSTS subject to min Env Costs	**\$ 354.68**	**70.8**	-	0%	2,008,700	100%	-	0%	**2,008,700**
min ENV costs subject to min Costs	**\$ 322.79**	**152.0**	6,339,440	100%	-	0%	-	0%	**6,339,440**

In the scenario of low demand (Table 30), by investing \$1.11 million more on pallet management systems, the total system environmental impact can be reduced by 2.9 metric KTons of CO_2 emissions. Likewise, in the scenario of high demand (Table 31), by increasing pallet management systems investment by \$32 million, half of the system environmental impact can be reduced.

When the system considers a slight difference in costs among the pallet types in the study, such as in purchase/leasing costs and selling prices/credits of return, as shown earlier in Table 27, different outputs are obtained. In the scenario when minimizing the system cost subject to minimum environmental

impact, pallets of type 3 are the only pallets manufactured. Furthermore, in the scenario where the system is minimized for total environmental impacts subject to minimum cost, a mix of pallets type 1 and type 3 (approximately 73 percent and 27 percent, respectively) are manufactured (Table 32). These results are expected since under this cost scenario both pallet types have very similar net cost ($4.75 for pallet type 1, and $5 for pallet type 3; compared to nominal net costs of $3 per type 1, and $5 per type 3). Similar pallet percentages were obtained when considering high pallet demand (Table 33). In general it can be concluded that the model outputs are not sensitive to demand

Table 32. Low demand - Costs modified from nominal values per pallet type

	System Cost (in million)	Total Environmental Impact (KTons CO_2)	New Pallets Manufactured						Total New Pallets Manufactured
			Pallet 1		Pallet 3		Pallet 4		
min COSTS subject to min Env Costs	**$ 12.71**	**2.6**	-	0%	70,755	100%	-	0%	**70,755**
min ENV costs subject to min Costs	**$ 12.59**	**4.5**	123,971	72%	48,611	28%	-	0%	**172,582**

Table 33. High demand - Costs modified from nominal values per pallet type

	System Cost (in million)	Total Environmental Impact (KTons CO_2)	New Pallets Manufactured						Total New Pallets Manufactured
			Pallet 1		Pallet 3		Pallet 4		
min COSTS subject to min Env Costs	**$ 358.77**	**72.9**	-	0%	2,008,700	100%	-	0%	**2,008,700**
min ENV costs subject to min Costs	**$ 355.07**	**134.4**	3,886,650	75%	1,309,990	25%	-	0%	**5,196,640**

5.2.6 DOES TRANSPORTATION AFFECT THE PREFERRED PALLET MANAGEMENT SYSTEM?

Various distances between distributor's facilities, such as distribution centers, retailers, and return center, are considered to analyze different pallet outcomes. These average distances ($L_{(i,j)}$) are: 30, 300, and 3,000 miles, as shown in Figure 24. It is expected that the pallet outcome does not get affected by the miles travelled, since the same distance will apply to each of the pallet types, and further, because the CO_2 footprint per mile from transportation from one pallet to another is slightly similar among the pallet types (see Appendix A).

FACTOR	PALLET 1/3/4		
Average Distance traveled within distributors' facilities per cycle (miles)	30	300	3,000

Figure 24. Levels for factor distance

Despite the distance between distributors' facilities, pallets type 3 are chosen in 100 percent when minimizing the system cost subject to minimum environmental impacts (for a time horizon of 6 months and 2 years). Furthermore, Figure 25 illustrates the results of the eco-audit for each distance. Here, for an average distance of 30 miles, the Material phase represents 84 percent of total system CO_2 footprint (2.78 metric KTons of CO_2), whereas, for an average distance of 3,000 miles, Transportation represents 76 percent of total system CO_2 footprint (11.07 metric KTons of CO_2).

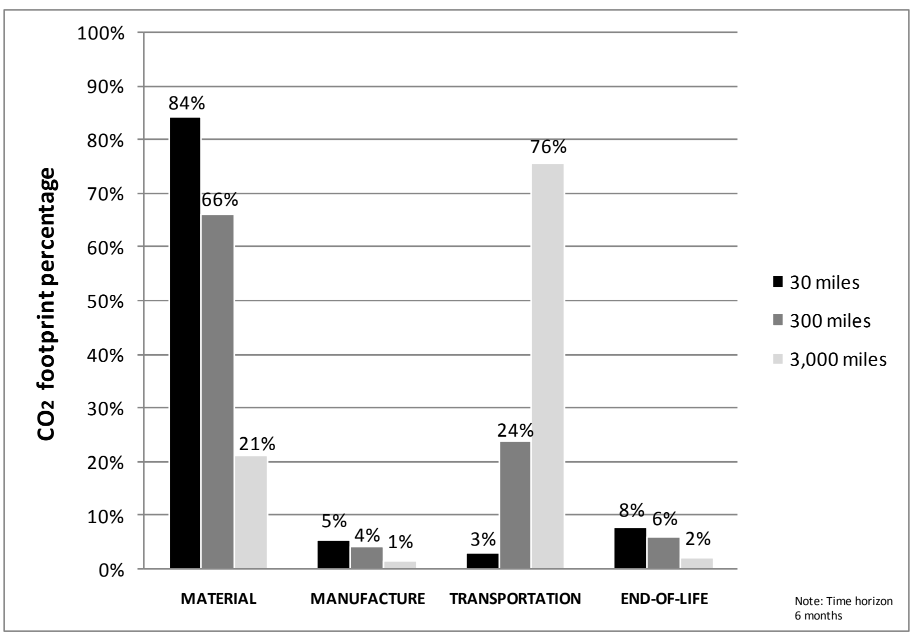


Figure 25. Eco-Audit when minimizing system cost subject to minimum environmental impacts for different distances per cycle (Time horizon: 6 months)

Figure 26 shows that purchase/leasing cost represents 76 percent of total system cost ($5.98 million) under the scenario of 30 miles; compared to the transportation cost which represents 96 percent of total system cost ($135.17 million) under the scenario of 3,000 miles. Note percentages are shown for a time horizon of 6 months; similar outputs were obtained considering a time horizon of 2 years.

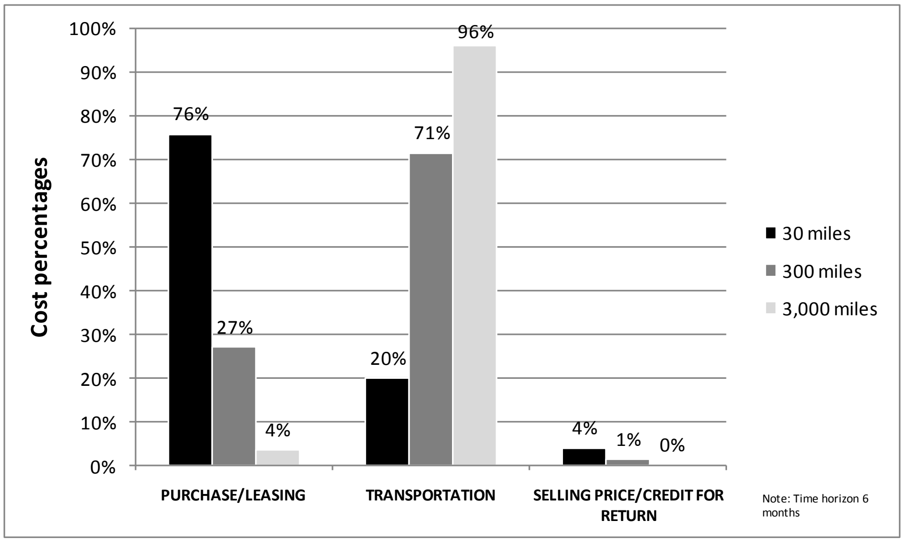


Figure 26. Cost breakdown when minimizing system cost subject to minimum environmental impacts for different distances per cycle (Time horizon: 6 months)

On the other hand, pallet type 1 is the only type chosen when minimizing the environmental impacts subject to minimum cost, because they are the less expensive pallet. Thus, when allowing pallet expenditures to increase by 20 percent the minimum cost while reducing the total system environmental impact, pallet type 3 is the only type manufactured for a time horizon of 6 months (that is, assuming a total distance of 3,000 miles). When assuming shorter distances, a mix of pallets type 1 and 3 are manufactured.

As general conclusion, the preferred pallet management system is not sensitive to transportation. In addition, the higher the distance the higher the impact of the Transportation phase.

5.2.7 How can new Regulations on pallet End-Of-Life Scenarios influence the system carbon footprint?

The model is flexible enough to consider possible new regulations regarding pallet end-of-life alternatives. For example, the state of North Carolina dictated a legislation to ban pallet landfilling in 2009 (Buehlmann et al., 2009). As this, other regulations could help protect the environment.

This section proposes the existence of a regulation which would declare that pallet landfilling would be banned, regardless the type of pallet, that wooden pallets have to be downcycled at 10 percent and plastic pallets have to be recycled at 100 percent (Figure 27). These percentages would affect the parameter $R_{p,d}$ in the model.

FACTORS	PALLET 1/3	PALLET 4
Wood Pallet: Downcycling % + Landfill % Plastic Pallet: Recycle % + Landfill %	10% 0%	100% 0%

Figure 27. Levels for factor pallet end-of-life scenarios

When minimizing total system cost subject to minimum environmental impacts, pallets of type 3 are the only type manufactured. Although, because this pallet type is repaired in higher percentage under the proposed regulation for a time horizon of 6 months, fewer pallets are needed, reducing the system environmental impact by 329 metric Tons of CO_2 emissions (approximately a 10 percent decrease). In addition, the cost is reduced by $248 thousands (a 1.4 percent decrease). Under a time horizon of 2 years the total environmental impact is reduced by 447 metric Tons of CO_2 (6.5 percent) and by $900 thousands (1.3 percent) of system cost (refer to Table 34).

Table 35 shows the number of pallets disposed to each of the end-of-life alternatives for a time horizon of 6 months. A higher number of pallets are repaired compared to the current scenario where no regulation is in place. Refer to Appendix D for results considering a time horizon of 2 years.

Table 34. Results comparison base scenario vs. regulation scenario when minimizing system cost subject to environmental impacts (Time horizon: 6 months and 2 years)

		Base Scenario		Scenario Regulation	
		Pallet Type / Landfill / Downc/Recycle: Pallet 1: 1%, 89% Pallet 3: 1%, 19% Pallet 4: 0%, 100%		Pallet Type / Landfill / Downc/Recycle: Pallet 1: 0%, 10% Pallet 3: 0%, 10% Pallet 4: 0%, 100%	
Time Horizon		6 months	2 years	6 months	2 years
Total System Environmental Impact (metric Tons CO2)		3,537	6,917	3,207	6,471
Total System Cost (in million)		$ 17.7	$ 71.2	$ 17.5	$ 70.3
Number of New Pallets Manufactured	Pallet 1	-	-	-	-
	Pallet 3	100,406	125,732	83,610	99,910
	Pallet 4	-	-	-	-
	Total Pallets	100,406	125,732	83,610	99,910

Table 35. End-of-life scenarios base scenario vs. regulation scenario when minimizing system cost subject to environmental impacts (Time horizon: 6 months)

		Base Scenario				Scenario Regulation			
		Pallet Type / Landfill / Downcycle/Recycle: Pallet 1: 1%, 89% Pallet 3: 1%, 19% Pallet 4: 0%, 100%				Pallet Type / Landfill / Downcycle/Recycle: Pallet 1: 0%, 10% Pallet 3: 0%, 10% Pallet 4: 0%, 100%			
Time Horizon		6 months				6 months			
Pallet Type in the System		Pallet 1	Total % per EOL	Pallet 3	Total % per EOL	Pallet 1	Total % per EOL	Pallet 3	Total % per EOL
Pallet End-of-Life Alternative	Repaired to reuse	2,419	10%	26,486	80%	53,328	90%	25,588	90%
	Recycled to reuse	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Downcycled	21,521	89%	6,291	19%	5,926	10%	2,844	10%
	Landfilled	242	1%	332	1%	-	0%	-	0%
	Incinerated	-	0%	-	0%	-	0%	-	0%

CONCLUSIONS AND FUTURE WORK

This section summarizes the findings and key elements that resulted from the research conducted. In addition, opportunities for future work and improvements are also discussed.

CONCLUSIONS

In current times companies are continuously making improvements of their operations efficiency and environmental performance. Efforts for reducing energy and carbon footprint from their supply chain management, such as shipping and distribution operations, have included minimizing waste, resource consumption, and overall GHG emissions. However, there is a need for effective and efficient optimization models which address pallet operations, considering pallet environmental impacts and costs within an entire supply chain.

This study addressed such a gap by providing a model that studies pallet life cycle stages and their operations, including raw materials, manufacture, use, and end-of-life scenarios, while embracing the pallet costs of the system. Such a model determines the mix of pallets (type, quantity, and pallet management system) for product distribution that balances overall environmental impacts (measured in carbon dioxide emissions) and costs according to companies' needs.

Issues that can drive the choice of a pallet management system are addressed in this study, such as the carbon dioxide footprint from materials production and pallet manufacturing, the emissions that arise during product transportation, the impacts associated with the various end-of-life alternatives available

for different pallet types (such as reuse, recycling, downcycling, repair, landfill, and incineration), and the costs of purchasing or leasing a pallet, as well as their selling prices or credits for returns.

The model was designed to give flexibility to the tool user to change parameters such as pallet characteristics (i.e. material, costs, etc.), and network changes, including the number of consumer product manufacturers, distribution centers, retailers, and return centers considered in the supply chain.

Pallet types (or pallet management systems) addressed in the study include: pallet type 1, a wooden pallet under buy/sell program; pallet types 2 and 3, pooled wooden pallets; and pallet type 4, a pooled plastic pallet. In addition, results were driven to cover the different pallet life cycle phases. Areas of analysis include: pallet materials and weights, pallet purchase/leasing costs, transportation distances, pallet demand, and pallet end-of-life alternatives.

The tradeoff between environmental impacts and costs was illustrated. For a time horizon of 1 year, when minimizing the system environmental impacts, the minimum amount of CO_2 released is 4,678 metric Tons under the assumptions stated; whereas, when minimizing the system cost the amount of CO_2 released is 14,052 metric Tons. As observed, by allowing the pallet expenditures to increase by 10.6 percent of the minimum (representing in this case a delta of $3.4 million), 9,374 metric Tons of CO_2 could be saved.

For the case study, when the system performs under nominal values and is minimized for the total environmental impacts while performing under the lowest cost, it was shown for short time horizons (up to 8 months) that pallet type 1 is the pallet preferred to satisfy the demand. For longer time horizons (up to 5 years) a mix of pallets type 1 and type 3 are manufactured.

When the system performs under a different scenario where costs can increase to 25 percent the minimum cost, the only pallet manufactured is type 3. In this case the system chooses a pallet management system that may cost more but whose pallets last longer.

Pallet weight and pallet purchase/leasing costs parameters were analyzed through an experiment. Results show that when minimizing the total system environmental impact subject to minimum cost, pallet weight under the factor levels studied does not affect the output of the model. In addition, the pallet that optimizes the system is the pallet type with the lowest purchase/leasing cost, whether it is pallet type 1, type 3 or type 4. On the other hand, when minimizing the system cost subject to minimum environmental costs, pallet type 3 is the pallet chosen as preferred.

Factors such as pallet weight and the CO_2 footprint from material primary production were analyzed when minimizing the system cost subject to the minimum environmental impacts. Pallets type 4 are the only pallet type manufactured when their weigh is 20 pounds per pallet and are made of all recycled material (recycled plastic and recycled steel for reinforcement bars). The higher the weight and the CO_2 footprint from material production for pallet type 4, the less these pallets are manufactured in the system. Consequently, pallets type 3 are preferred when pallets type 4 weigh 35 pounds per pallet or more, and when they are made of raw materials (plastic and steel) or only raw plastic.

Furthermore, the system was analyzed under different pallet demands and transportation distances. From the experiments it was noted that the outcome was not directly affected by either of these factors. As a result, it was concluded that neither pallet demand nor transportation distances affect the choice of pallet management.

The model allows considering possible new regulations regarding pallets end-of-life alternatives. Consequently, different experiments were modeled considering if new regulations were to require that pallets cannot be sent in any amount to a landfill, while wooden pallets are downcycled at 10 percent and plastic pallets are recycled at 100 percent. Results show pallet type 3 to be the only pallet manufactured when minimizing the total system cost while minimizing environmental impacts. In addition, the total carbon footprint could be reduced by 10 percent.

As a result of these analyses, it can be concluded that this work provides a decision making tool for companies seeking to engage in more sustainable practices in their supply chains and distribution. It could help pallet users reach their goals of CO_2 footprint reduction while using an environmental and cost effective pallet management system. Moreover, pallet providers may be motivated to improve their pallet design and provide an efficient logistic that will address sustainable concerns to stay competitive in the market.

In addition, this study was an effort to build better understanding of pallet materials that have been under controversy and debate, providing deeper understanding in the importance of pallet operations *per se*. This research provides the tool to determine where efforts have to be focused and where users can make better decisions to ensure and preserve the environment.

FUTURE WORK

There are different areas that could be improved in the future and which could contribute to a larger research scope in understanding more complex systems to decrease the system environmental impact and its costs. Potential opportunities for improvements are discussed below.

The study evaluates the environmental impacts of pallet manufacturing, use, and disposal with respect to all aspects of sustainability, emphasizing the carbon footprint (in particular CO_2) of the operations. Future work could include impacts to human health, biodiversity, and eco-system depletion, which may reveal interesting aspects of the model. In addition, pallet toxicity due to flame retardants (in plastic pallets) and fumigation chemicals (for wooden pallets) could be modeled as a pallet characteristic.

Results were shown for the case study of a local grocery distributor/retailer. Transportation was not taken into account between consumer product manufacturers and pallet distributor. Moreover, future

work could target studying more complex systems with specific and detailed information on facilities' locations, also including different cost scenarios.

This thesis focused on studying the use of wooden and plastic pallets in the grocery industry. Metal pallets or other type of pallets, made of different materials and/or with different structures, could be addressed to see pallet choices preferences and system environmental impacts.

Further, policy making decisions could be addressed, such as regulations applied to pallets end-of-life alternatives and carbon tax credits.

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APPENDICES

A. Validation and Case Study Input Data

Table 36. Carbon dioxide footprint from material primary production per pallet type

	Material	Weight (lbs)	MATERIAL CO_2 Footprint: lbs CO_2/lb	MATERIAL CO_2 Footprint: lbs CO_2
Pallet 1	Hardwood Oak: medium density	42	0.4495	18.8790
	Low Alloy Steel: Zn-Cu alloy, fastener wire	3	4.5800	13.7400
	Total per Pallet 1	**45**		**32.6190**
Pallet 2	Hardwood Oak: medium density	62	0.4495	27.8690
	Low Alloy Steel: Zn-Cu alloy, fastener wire	3	4.5800	13.7400
	Total per Pallet 2	**65**		**41.6090**
Pallet 3	Hardwood Oak: medium density	59	0.4495	26.5205
	Low Alloy Steel: Zn-Cu alloy, fastener wire	3	4.5800	13.7400
	Total per Pallet 3	**62**		**40.2605**
Pallet 4	HDPE: high-density homopolymer	38.36	2.0500	78.6380
	Low Carbon Steel: AISI 10101, annealed	9.14	2.4850	22.7129
	Total per Pallet 4	**47.5**		**101.3509**

Table 37. Carbon dioxide footprint from pallet manufacture per pallet type

	Material	Manufacturing Process	Weight (lbs)	MANUFACTURE CO_2 Footprint: lbs CO_2/lb	MANUFACTURE CO_2 Footprint: lbs CO_2
Pallet 1	Hardwood Oak	Assembly and Construction	42	0.0400	1.6800
	Low Alloy Steel	Casting	3	0.0669	0.2007
		Total per Pallet 1	**45**		**1.8807**
Pallet 2	Hardwood Oak	Assembly and Construction	62	0.0400	2.4800
	Low Alloy Steel	Casting	3	0.0669	0.2007
		Total per Pallet 2	**65**		**2.6807**
Pallet 3	Hardwood Oak	Assembly and Construction	59	0.0400	2.3600
	Low Alloy Steel	Casting	3	0.0669	0.2007
		Total per Pallet 3	**62**		**2.5607**
Pallet 4	HDPE	Injection Molding	38.36	0.5165	19.8129
	Low Carbon Steel	Casting	9.14	0.2645	2.4175
		Total per Pallet 4	**47.5**		**22.2305**

Table 38. Carbon dioxide footprint from transportation per pallet type

		TRANSPORTATION CO_2 Footprint	
	Weight (lbs)	lbs CO_2/ lbs-mile	lbs CO_2/ mile
Pallet 1	45	0.0001697	0.0076365
Pallet 2	65	0.0001175	0.0076375
Pallet 3	62	0.0001232	0.0076384
Pallet 4	47.5	0.0001608	0.0076380

Table 39. Carbon dioxide footprint from end-of-life life-cycle stage per pallet type

			PALLETS END-OF-LIFE									
			Repair (Wooden Pallets)		Recycling (Plastic Pallets)		Downcycling (Wooden Pallets)		Landfill (Wood and Plastic Pallets)		Incineration (Wood and Plastic Pallets)	
	Material	Weight (lbs)	Material Disposal Scenario	lbs CO_2	Material Disposal Scenario	lbs CO_2	Material Disposal Scenario	lbs CO_2	Material Disposal Scenario	lbs CO_2	Material Disposal Scenario	lbs CO_2
Pallet 1	**Hardwood Oak**	42	Wood Repair	1.8879	N/A		Wood Downcycling	7.5516	Wood Landfill	18.8790	Wood Incinerated	72.8700
	Low Alloy Steel	3	Steel Recycling	2.4705	N/A		Steel Recycling	2.4705	Steel Landfill	13.7400	Steel Landfill	13.7400
	Total per Pallet 1	**45**		**4.3584**				**10.0221**		**32.6190**		**86.6100**
Pallet 2	**Hardwood Oak**	62	Wood Repair	2.7869	N/A		Wood Downcycling	11.1476	Wood Landfill	27.8690	Wood Incinerated	107.5700
	Low Alloy Steel	3	Steel Recycling	2.4705	N/A		Steel Recycling	2.4705	Steel Landfill	13.7400	Steel Landfill	13.7400
	Total per Pallet 2	**65**		**5.2574**				**13.6181**		**41.6090**		**121.3100**
Pallet 3	**Hardwood Oak**	59	Wood Repair	2.6521	N/A		Wood Downcycling	10.6082	Wood Landfill	26.5205	Wood Incinerated	102.3650
	Low Alloy Steel	3	Steel Recycling	2.4705	N/A		Steel Recycling	2.4705	Steel Landfill	13.7400	Steel Landfill	13.7400
	Total per Pallet 3	**62**		**5.1226**				**13.0787**		**40.2605**		**116.1050**
Pallet 4	**HDPE**	38.36	N/A		Plastic Recycling	19.1800	N/A		Plastic Landfill	78.6380	N/A	
	Low Carbon Steel	9.14	N/A		Steel Recycling	6.3523	N/A		Steel Landfill	22.7129	N/A	
	Total per Pallet 4	**47.5**				**25.5323**				**101.3509**		

B. Detailed Multi-Objective Optimization Model in AMPL, time horizon: 6 months

Model File

```
### SETS ###

set P := 1..4;   # set of type of pallets
set N := 1..2;   # set of materials (m1, m2)
set D := 1..6;   # disposal scenario (reuse, repair, recycle, downcycling, landfill, incineration)
set T := 0..26;   # time periods (weeks)

set G;
set RM;
set MP;
set CPM;
set DC;
set RET := 1..75;
set RC;
set DEOL;
set LEOL;
set IEOL;

set Nodes:= G union RM union MP union CPM union DC union RET union RC union DEOL union LEOL union
IEOL;

set DC_RET_Arcs within (DC cross RET);

set Arcs:= (G cross RM) union (RM cross MP) union (MP cross CPM) union (CPM cross DC) union
DC_RET_Arcs union (RET cross RC) union (DC cross CPM) union (DC cross MP) union (DC cross RM) union
(DC cross DEOL) union (DC cross LEOL) union (DC cross IEOL) union (RC cross CPM) union (RC cross MP)
union (RC cross RM) union (RC cross DEOL) union (RC cross LEOL) union (RC cross IEOL);

set ArcsDiffTime := (CPM cross DC) union DC_RET_Arcs union (DC cross CPM) union (RC cross CPM) union
(DC cross MP) union (DC cross RM) union (DC cross DEOL) union (DC cross LEOL) union (DC cross IEOL)
union (RC cross MP) union (RC cross RM) union (RC cross DEOL) union (RC cross LEOL) union (RC cross
IEOL);

set ArcsSameTime := Arcs diff ArcsDiffTime;
```

```
### PARAMETERS ###

param W {p in P, n in N, (i,j) in Arcs}:= (if (p==1) then (if (n=1 and (i,j) in Arcs) then 42 else 3)
        else if (p==2) then (if (n=1 and (i,j) in Arcs) then 62 else 3)
        else if (p==3) then (if (n=1 and (i,j) in Arcs) then 59 else 3)
        else          (if (n=1 and (i,j) in Arcs) then 38.36 else 9.14)
        );    #weight per pallet type p in lbs


# ENVIRONMENTAL PARAMETERS

param M {p in P, n in N, (i,j) in Arcs}:= (if (p==1) then (if (n=1) then (if ((i,j) in Arcs and i=='G' and j=='RM') then
0.4495
                else 0)
        else (if ((i,j) in Arcs and i=='G' and j=='RM') then 4.58
                else 0))
    else if (p==2) then (if (n=1) then (if ((i,j) in Arcs and i=='G' and j=='RM') then 0.4495
                else 0)
        else (if ((i,j) in Arcs and i=='G' and j=='RM') then 4.58
                else 0))
    else if (p==3) then (if (n=1) then (if ((i,j) in Arcs and i=='G' and j=='RM') then 0.4495
                else 0)
        else (if ((i,j) in Arcs and i=='G' and j=='RM') then 4.58
                else 0))
    else (if (n=1) then (if ((i,j) in Arcs and i=='G' and j=='RM') then 2.05
                else 0)
        else (if ((i,j) in Arcs and i=='G' and j=='RM') then 2.485
                else 0))
        );      #material env imp per lb


param Mfg {p in P, n in N, (i,j) in Arcs}:= (if (p==1) then (if (n=1) then (if ((i,j) in Arcs and i=='RM' and j=='MP')
then 0.04
                else 0)
        else (if ((i,j) in Arcs and i=='RM' and j=='MP') then 0.0669
                else 0))
```

```
else if (p==2) then (if (n=1) then (if ((i,j) in Arcs and i=='RM' and j=='MP') then 0.04
                else 0)
        else (if ((i,j) in Arcs and i=='RM' and j=='MP') then 0.0669
                else 0))
else if (p==3) then (if (n=1) then (if ((i,j) in Arcs and i=='RM' and j=='MP') then 0.04
                else 0)
        else (if ((i,j) in Arcs and i=='RM' and j=='MP') then 0.0669
                else 0))
else (if (n=1) then (if ((i,j) in Arcs and i=='RM' and j=='MP') then 0.5165
                else 0)
        else (if ((i,j) in Arcs and i=='RM' and j=='MP') then 0.2645
                else 0))
        );      #manufacturing env imp per lb



param EOL {p in P, n in N, (i,j) in Arcs}:= (if (p==1) then (if (n==1) then (if ((i,j) in Arcs and i in DC and j=='MP')
then 0.04495
                else if ((i,j) in Arcs and i in DC and j=='DEOL') then 0.18
                else if ((i,j) in Arcs and i in DC and j=='LEOL') then 0.4495
                else if ((i,j) in Arcs and i in DC and j=='IEOL') then 1.735
                else if ((i,j) in Arcs and i=='RC' and j=='MP') then 0.04495
                else if ((i,j) in Arcs and i=='RC' and j=='DEOL') then 0.18
                else if ((i,j) in Arcs and i=='RC' and j=='LEOL') then 0.4495
                else if ((i,j) in Arcs and i=='RC' and j=='IEOL') then 1.735
                else 0)
        else (if ((i,j) in Arcs and i in DC and j=='MP') then 0.8235
                else if ((i,j) in Arcs and i in DC and j=='DEOL') then 0.8235
                else if ((i,j) in Arcs and i in DC and j=='LEOL') then 4.58
                else if ((i,j) in Arcs and i in DC and j=='IEOL') then 4.58
                else if ((i,j) in Arcs and i=='RC' and j=='MP') then 0.8235
                else if ((i,j) in Arcs and i=='RC' and j=='DEOL') then 0.8235
                else if ((i,j) in Arcs and i=='RC' and j=='LEOL') then 4.58
                else if ((i,j) in Arcs and i=='RC' and j=='IEOL') then 4.58
                else 0))
else if (p==2) then (if (n==1) then (if ((i,j) in Arcs and i in DC and j=='MP') then 0.04495
                else if ((i,j) in Arcs and i in DC and j=='DEOL') then 0.18
```

```
                    else if ((i,j) in Arcs and i in DC and j=='LEOL') then 0.4495
                    else if ((i,j) in Arcs and i in DC and j=='IEOL') then 1.735
                    else if ((i,j) in Arcs and i=='RC' and j=='MP') then 0.04495
                    else if ((i,j) in Arcs and i=='RC' and j=='DEOL') then 0.18
                    else if ((i,j) in Arcs and i=='RC' and j=='LEOL') then 0.4495
                    else if ((i,j) in Arcs and i=='RC' and j=='IEOL') then 1.735
                    else 0)
          else (if ((i,j) in Arcs and i in DC and j=='MP') then 0.8235
                    else if ((i,j) in Arcs and i in DC and j=='DEOL') then 0.8235
                    else if ((i,j) in Arcs and i in DC and j=='LEOL') then 4.58
                    else if ((i,j) in Arcs and i in DC and j=='IEOL') then 4.58
                    else if ((i,j) in Arcs and i=='RC' and j=='MP') then 0.8235
                    else if ((i,j) in Arcs and i=='RC' and j=='DEOL') then 0.8235
                    else if ((i,j) in Arcs and i=='RC' and j=='LEOL') then 4.58
                    else if ((i,j) in Arcs and i=='RC' and j=='IEOL') then 4.58
                    else 0))
else if (p==3) then (if (n==1) then (if ((i,j) in Arcs and i in DC and j=='MP') then 0.04495
                    else if ((i,j) in Arcs and i in DC and j=='DEOL') then 0.18
                    else if ((i,j) in Arcs and i in DC and j=='LEOL') then 0.4495
                    else if ((i,j) in Arcs and i in DC and j=='IEOL') then 1.735
                    else if ((i,j) in Arcs and i=='RC' and j=='MP') then 0.04495
                    else if ((i,j) in Arcs and i=='RC' and j=='DEOL') then 0.18
                    else if ((i,j) in Arcs and i=='RC' and j=='LEOL') then 0.4495
                    else if ((i,j) in Arcs and i=='RC' and j=='IEOL') then 1.735
                    else 0)
          else (if ((i,j) in Arcs and i in DC and j=='MP') then 0.8235
                    else if ((i,j) in Arcs and i in DC and j=='DEOL') then 0.8235
                    else if ((i,j) in Arcs and i in DC and j=='LEOL') then 4.58
                    else if ((i,j) in Arcs and i in DC and j=='IEOL') then 4.58
                    else if ((i,j) in Arcs and i=='RC' and j=='MP') then 0.8235
                    else if ((i,j) in Arcs and i=='RC' and j=='DEOL') then 0.8235
                    else if ((i,j) in Arcs and i=='RC' and j=='LEOL') then 4.58
                    else if ((i,j) in Arcs and i=='RC' and j=='IEOL') then 4.58
                    else 0))
else            (if (n==1) then (if ((i,j) in Arcs and i in DC and j=='RM') then 0.5
```

```
                    else if ((i,j) in Arcs and i in DC and j=='LEOL') then 2.05
                    else if ((i,j) in Arcs and i in DC and j=='IEOL') then 3.14
                    else if ((i,j) in Arcs and i=='RC' and j=='RM') then 0.5
                    else if ((i,j) in Arcs and i=='RC' and j=='LEOL') then 2.05
                    else if ((i,j) in Arcs and i=='RC' and j=='IEOL') then 3.14
                    else 0)
            else (if ((i,j) in Arcs and i in DC and j=='RM') then 0.695
                    else if ((i,j) in Arcs and i in DC and j=='LEOL') then 2.485
                    else if ((i,j) in Arcs and i in DC and j=='IEOL') then 2.485
                    else if ((i,j) in Arcs and i=='RC' and j=='RM') then 0.695
                    else if ((i,j) in Arcs and i=='RC' and j=='LEOL') then 2.485
                    else if ((i,j) in Arcs and i=='RC' and j=='IEOL') then 2.485
                    else 0))
            );      #env imp per endoflife per pallet type p


# COST PARAMETERS

param CO {p in P, (i,j) in Arcs}:= (if (p==1) then (if ((i,j) in Arcs and i=='MP' and j in CPM) then 5
            else if ((i,j) in Arcs and i in DC and j in CPM) then 5
            else if ((i,j) in Arcs and i=='RC' and j in CPM) then 5
            else 0)
        else if (p==2) then (if ((i,j) in Arcs and i=='MP' and j in CPM) then 5.8
            else if ((i,j) in Arcs and i in DC and j in CPM) then 5.8
            else if ((i,j) in Arcs and i=='RC' and j in CPM) then 5.8
            else 0)
        else if (p==3) then (if ((i,j) in Arcs and i=='MP' and j in CPM) then 5
            else if ((i,j) in Arcs and i in DC and j in CPM) then 5
            else if ((i,j) in Arcs and i=='RC' and j in CPM) then 5
            else 0)
        else        (if ((i,j) in Arcs and i=='MP' and j in CPM) then 6
            else if ((i,j) in Arcs and i in DC and j in CPM) then 6
            else if ((i,j) in Arcs and i=='RC' and j in CPM) then 6
            else 0)
            );    #purchasing/leasing cost for pallet type p
```

```
param S {p in P, (i,j) in Arcs}:= (if (p==1) then (if ((i,j) in Arcs and i in DC and j in CPM) then 2
                    else if ((i,j) in Arcs and i in DC and j=='MP') then 2
                    else if ((i,j) in Arcs and i in DC and j=='DEOL') then 2
                    else if ((i,j) in Arcs and i in DC and j=='LEOL') then 2
                    else if ((i,j) in Arcs and i in DC and j=='IEOL') then 2
                    else if ((i,j) in Arcs and i=='RC' and j in CPM) then 2
                    else if ((i,j) in Arcs and i=='RC' and j=='MP') then 2
                    else if ((i,j) in Arcs and i=='RC' and j=='DEOL') then 2
                    else if ((i,j) in Arcs and i=='RC' and j=='LEOL') then 2
                    else if ((i,j) in Arcs and i=='RC' and j=='IEOL') then 2
                    else 0)
          else if (p==4) then (if ((i,j) in Arcs and i in DC and j in CPM) then 0.25
                    else if ((i,j) in Arcs and i in DC and j=='RM') then 0.25
                    else if ((i,j) in Arcs and i in DC and j=='LEOL') then 0.25
                    else if ((i,j) in Arcs and i in DC and j=='IEOL') then 0.25
                    else if ((i,j) in Arcs and i=='RC' and j in CPM) then 0.25
                    else if ((i,j) in Arcs and i=='RC' and j=='RM') then 0.25
                    else if ((i,j) in Arcs and i=='RC' and j=='LEOL') then 0.25
                    else if ((i,j) in Arcs and i=='RC' and j=='IEOL') then 0.25
                    else 0)
          else 0);     #credit for selling pallets or returning empty leased pallets ($/pallet)


param CT {p in P, (i,j) in Arcs}:= (if (p==1) then (if ((i,j) in Arcs and i in DC and j in RET) then 0.1104
                    else if ((i,j) in Arcs and i in RET and j=='RC') then 0.0055
                    else 0)
          else if (p==2) then (if ((i,j) in Arcs and i in DC and j in RET) then 0.1104
                    else if ((i,j) in Arcs and i in RET and j=='RC') then 0.0055
                    else if ((i,j) in Arcs and i in DC and j in CPM) then 0.07
                    else if ((i,j) in Arcs and i in DC and j=='MP') then 0.07
                    else if ((i,j) in Arcs and i in DC and j=='DEOL') then 0.07
                    else if ((i,j) in Arcs and i in DC and j=='LEOL') then 0.07
                    else if ((i,j) in Arcs and i in DC and j=='IEOL') then 0.07
                    else if ((i,j) in Arcs and i=='RC' and j in CPM) then 0.07
                    else if ((i,j) in Arcs and i=='RC' and j=='MP') then 0.07
```

```
            else if ((i,j) in Arcs and i=='RC' and j=='DEOL') then 0.07
            else if ((i,j) in Arcs and i=='RC' and j=='LEOL') then 0.07
            else if ((i,j) in Arcs and i=='RC' and j=='IEOL') then 0.07
            else 0)
      else if (p==3) then (if ((i,j) in Arcs and i in DC and j in RET) then 0.1104
            else if ((i,j) in Arcs and i in RET and j=='RC') then 0.0055
            else 0)
      else            (if ((i,j) in Arcs and i in DC and j in RET) then 0.1104
            else if ((i,j) in Arcs and i in RET and j=='RC') then 0.0055
            else 0)
            );      #cost of transportation ($/mile)


#OTHER PARAMETERS

param Q {p in P, i in DC} >= 0; #pre-position inventory at nodes
param ET {p in P} ; #env imp of transportation
param fdc {p in P};         # FAILURE  percent from DC per pallet type
param frc {p in P};         # FAILURE  percent from RC per pallet type
param R {p in P, d in D} default 0; #pallet end of life fraction
param L {Arcs} default 0; #distance in miles from i to j
param Dc {DC,T}; #pallet demand per DC at time t
param Db {DC,RET,T}; #total pallet demand in retailers
param Z;
param h; #rate of cost increase
param e {p in P, n in N, (i,j) in Arcs}:= M[p,n,i,j]*W[p,n,i,j] + Mfg[p,n,i,j]*W[p,n,i,j] + ET[p]*W[p,n,i,j]*L[i,j] +
EOL[p,n,i,j]*W[p,n,i,j]; #carbon footprint
param C {p in P, (i,j) in Arcs}:= CO[p,i,j] + CT[p,i,j]*L[i,j] - S[p,i,j];   #cost ($)

check {p in P}: sum {d in D} R[p,d] = 1;   #checking that all EOLs together for each pallet type add up to 1
### VARIABLES ###

var Y {p in P, (i,j) in Arcs, t1 in T, t2 in T: t2 <= t1+1 and t2 >= t1} >= 0;  #pallet flow per type p from nodes i to j
at time t

var Inv {p in P, i in DC, t in T} >= 0;    # number of pallets inventoried at time t
```

OBJECTIVE FUNCTIONS

minimize Cost: sum {p in P, (i,j) in Arcs, t in T} C[p,i,j] * Y[p,i,j,t,t] + sum {p in P, (i,j) in Arcs, t in T: t < 26} C[p,i,j]*Y[p,i,j,t,t+1];

minimize Environmental_Cost: sum {p in P, n in N, (i,j) in Arcs, t in T} e[p,n,i,j]*Y[p,i,j,t,t] + sum {p in P, n in N, (i,j) in Arcs, t in T: t < 26} e[p,n,i,j]*Y[p,i,j,t,t+1] + sum {p in P, n in N, i in DC} (M[p,n,'G','RM'] + Mfg[p,n,'RM','MP'])*W[p,n,'G','RM']*Q[p,i];

#Total System Costs parameterized constraint

subject to Costs: sum {p in P, (i,j) in Arcs, t in T} C[p,i,j] * Y[p,i,j,t,t] + sum {p in P, (i,j) in Arcs, t in T: t < 26} C[p,i,j]*Y[p,i,j,t,t+1] <= Z * (1+h);

#Total System Environmental Burden parameterized constraint

subject to Env_Cost: sum {p in P, n in N, (i,j) in Arcs, t in T} e[p,n,i,j]*Y[p,i,j,t,t] + sum {p in P, n in N, (i,j) in Arcs, t in T: t < 26} e[p,n,i,j]*Y[p,i,j,t,t+1] + sum {p in P, n in N, i in DC} (M[p,n,'G','RM'] + Mfg[p,n,'RM','MP'])*W[p,n,'G','RM']*Q[p,i] <= Z * (1+h);

CONSTRAINTS

Number of pallets required to fulfill demand in distribution centers

subject to Demand_DC {j in DC, t in T: t < 26}: sum {p in P, i in CPM: (i,j) in ArcsDiffTime} Y[p,i,j,t,t+1] >= Dc[j,t+1];

Number of pallets required to fulfill demand in Retailers

subject to Demand_Retailers {i in DC, j in RET, t in T: (i,j) in ArcsDiffTime and t < 26}: sum {p in P} Y[p,i,j,t,t+1] >= Db[i,j,t+1];

Initial inventory must equal given value

subject to Initial_Inventory {p in P, i in DC, t in T: t==0}: Inv[p,i,t] == Q[p,i];

#RM Nodes balance constraints

subject to RM_Nodes_Balance_0 {p in P, k in RM, t in T: t==0}: sum {(i,k) in ArcsSameTime} Y[p,i,k,t,t] - sum {(k,j) in ArcsSameTime} Y[p,k,j,t,t] == 0;

subject to RM_Nodes_Balance {p in P, k in RM, t in T: t>0 and t<=26}: sum {(i,k) in ArcsSameTime} Y[p,i,k,t,t] + sum {(i,k) in ArcsDiffTime} Y[p,i,k,t-1,t] - sum {(k,j) in ArcsSameTime} Y[p,k,j,t,t] == 0;

#MP Nodes balance constraints

subject to MP_Nodes_Balance_0 {p in P, k in MP, t in T: t==0}: sum {(i,k) in ArcsSameTime} Y[p,i,k,t,t] - sum {(k,j) in ArcsSameTime} Y[p,k,j,t,t] == 0;

subject to MP_Nodes_Balance {p in P, k in MP, t in T: t>0 and t<=26}: sum {(i,k) in ArcsSameTime} Y[p,i,k,t,t] + sum {(i,k) in ArcsDiffTime} Y[p,i,k,t-1,t] - sum {(k,j) in ArcsSameTime} Y[p,k,j,t,t] == 0;

#CPM Nodes balance constraints

subject to CPM_Nodes_Balance_0 {p in P, k in CPM, t in T: t==0}: sum {(i,k) in ArcsSameTime} Y[p,i,k,t,t] - sum {(k,j) in ArcsDiffTime} Y[p,k,j,t,t+1]== 0;

subject to CPM_Nodes_Balance {p in P, k in CPM, t in T: t>0 and t<26}: sum {(i,k) in ArcsSameTime} Y[p,i,k,t,t] + sum {(i,k) in ArcsDiffTime} Y[p,i,k,t-1,t] - sum {(k,j) in ArcsDiffTime} Y[p,k,j,t,t+1]== 0;

subject to CPM_Nodes_Balance_5 {p in P, k in CPM, t in T: t==26}: sum {(i,k) in ArcsSameTime} Y[p,i,k,t,t] + sum {(i,k) in ArcsDiffTime} Y[p,i,k,t-1,t] >= 0;

#DC Nodes balance constraints

subject to DC_Nodes_Balance_0 {p in P, k in DC, t in T: t==0}: Inv[p,k,t] - sum {(k1,j) in ArcsDiffTime: k1 == k} Y[p,k1,j,t,t+1] - Inv[p,k,t+1] == 0;

subject to DC_Nodes_Balance {p in P, k in DC, t in T: t>0 and t<26}: Inv[p,k,t] + sum {(i,k1) in ArcsDiffTime: k1 == k} Y[p,i,k1,t-1,t] - sum {(k1,j) in ArcsDiffTime: k1 == k} Y[p,k1,j,t,t+1] - Inv[p,k,t+1] == 0;

subject to DC_Nodes_Balance_5 {p in P, k in DC, t in T: t==26}: Inv[p,k,t] + sum {(i,k1) in ArcsDiffTime: k1 == k} Y[p,i,k1,t-1,t] >= 0;

#RET Nodes balance constraints

subject to RET_Nodes_Balance_0 {p in P, k in RET, t in T: t==0}: sum {(k,j) in ArcsSameTime} Y[p,k,j,t,t] == 0;

subject to RET_Nodes_Balance {p in P, k in RET, t in T: t>0 and t<=26}: sum {(i,k) in ArcsDiffTime} Y[p,i,k,t-1,t] - sum {(k,j) in ArcsSameTime} Y[p,k,j,t,t] == 0;

#RC Nodes balance constraints

subject to RC_Nodes_Balance {p in P, k in RC, t in T: t>=0 and t<26}: sum {(i,k) in ArcsSameTime} Y[p,i,k,t,t] - sum {(k,j) in ArcsDiffTime} Y[p,k,j,t,t+1] == 0;

subject to RC_Nodes_Balance_5 {p in P, k in RC, t in T: t==26}: sum {(i,k) in ArcsSameTime} Y[p,i,k,t,t] >= 0;

```
# Constraint for FAILURE percentage of Pallet type p out of DC

subject to FailureDC {p in P, t in T: t<25}: sum {(k,j) in ArcsDiffTime: (k in DC) and (j in RM or j in MP or j in DEOL or j in LEOL or j in IEOL)} Y[p,k,j,t+1,t+2] >= fdc[p]*sum {(i,k) in ArcsDiffTime: (i in CPM) and (k in DC)} Y[p,i,k,t,t+1];

subject to FailureRC {p in P, t in T: t<25}: sum {(k,j) in ArcsDiffTime: (k in RC) and (j in RM or j in MP or j in DEOL or j in LEOL or j in IEOL)} Y[p,k,j,t,t+1] >= frc[p]*sum {(i,k) in ArcsSameTime: (i in RET) and (k in RC)} Y[p,i,k,t,t];

#EOL flow per pallet type p

subject to RepairDC {p in P, t in T: p<4 and t<25}: sum {(a,c) in ArcsDiffTime: (a in DC) and (c in MP)} Y[p,a,c,t+1,t+2] <= R[p,2]*fdc[p]*sum {(a,c) in ArcsDiffTime: (a in CPM) and (c in DC)} Y[p,a,c,t,t+1];

subject to RepairRC {p in P, t in T: p<4 and t<26}: sum {(a,c) in ArcsDiffTime: (a in RC) and (c in MP)} Y[p,a,c,t,t+1] <= R[p,2]*frc[p]*sum {(a,c) in ArcsSameTime: (a in RET) and (c in RC)} Y[p,a,c,t,t];

subject to RecycleDC {p in P, t in T: p==4 and t<25}: sum {(a,c) in ArcsDiffTime: (a in DC) and (c in RM)} Y[p,a,c,t+1,t+2] <= R[p,3]*fdc[p]*sum {(a,c) in ArcsDiffTime: (a in CPM) and (c in DC)} Y[p,a,c,t,t+1];

subject to RecycleRC {p in P, t in T: p==4 and t<26}: sum {(a,c) in ArcsDiffTime: (a in RC) and (c in RM)} Y[p,a,c,t,t+1] <= R[p,3]*frc[p]*sum {(a,c) in ArcsSameTime: (a in RET) and (c in RC)} Y[p,a,c,t,t];

subject to DowncycleDC {p in P, t in T: p<4 and t<25}: sum {(a,c) in ArcsDiffTime: (a in DC) and (c in DEOL)} Y[p,a,c,t+1,t+2] <= R[p,4]*fdc[p]*sum {(a,c) in ArcsDiffTime: (a in CPM) and (c in DC)} Y[p,a,c,t,t+1];

subject to DowncycleRC {p in P, t in T: p<4 and t<26}: sum {(a,c) in ArcsDiffTime: (a in RC) and (c in DEOL)} Y[p,a,c,t,t+1] <= R[p,4]*frc[p]*sum {(a,c) in ArcsSameTime: (a in RET) and (c in RC)} Y[p,a,c,t,t];

subject to LandfillDC {p in P, t in T: t<25}: sum {(a,c) in ArcsDiffTime: (a in DC) and (c in LEOL)} Y[p,a,c,t+1,t+2] <= R[p,5]*fdc[p]*sum {(a,c) in ArcsDiffTime: (a in CPM) and (c in DC)} Y[p,a,c,t,t+1];

subject to LandfillRC {p in P, t in T: t<26}: sum {(a,c) in ArcsDiffTime: (a in RC) and (c in LEOL)} Y[p,a,c,t,t+1] <= R[p,5]*frc[p]*sum {(a,c) in ArcsSameTime: (a in RET) and (c in RC)} Y[p,a,c,t,t];

subject to IncinerationDC {p in P, t in T: t<25}: sum {(a,c) in ArcsDiffTime: (a in DC) and (c in IEOL)} Y[p,a,c,t+1,t+2] <= R[p,6]*fdc[p]*sum {(a,c) in ArcsDiffTime: (a in CPM) and (c in DC)} Y[p,a,c,t,t+1];

subject to IncinerationRC {p in P, t in T: t<26}: sum {(a,c) in ArcsDiffTime: (a in RC) and (c in IEOL)} Y[p,a,c,t,t+1] <= R[p,6]*frc[p]*sum {(a,c) in ArcsSameTime: (a in RET) and (c in RC)} Y[p,a,c,t,t];
```

```
#Fix unexisting variables to zero

subject to Fix0 {p in P, (i,j) in ArcsDiffTime, t in T: p<4 and (i in DC or i in RC) and (j in RM) and t<26}: Y[p,i,j,t,t+1] = 0;


subject to Fix1 {(i,j) in ArcsDiffTime, t in T: (i in DC or i in RC) and (j in MP or j in DEOL) and t<26}: Y[4,i,j,t,t+1] = 0;


subject to Fixttp1 {p in P,(i,j) in ArcsSameTime, t in T: t < 26}: Y[p,i,j,t,t+1]=0;


subject to Fixtt {p in P,(i,j) in ArcsDiffTime, t in T}: Y[p,i,j,t,t]=0;


subject to Repair0 {p in P, t in T: t==0}: sum {(a,c) in ArcsDiffTime: (a in DC) and (c in MP)} Y[p,a,c,t,t+1] = 0;


subject to Recycle0 {p in P, t in T: t==0}: sum {(a,c) in ArcsDiffTime: (a in DC) and (c in RM)} Y[p,a,c,t,t+1] = 0;


subject to Downcycle0 {p in P, t in T: t==0}: sum {(a,c) in ArcsDiffTime: (a in DC) and (c in DEOL)} Y[p,a,c,t,t+1] = 0;


subject to Landfill0 {p in P, t in T: t==0}: sum {(a,c) in ArcsDiffTime: (a in DC) and (c in LEOL)} Y[p,a,c,t,t+1] = 0;

subject to Incineration0 {p in P, t in T: t==0}: sum {(a,c) in ArcsDiffTime: (a in DC) and (c in IEOL)} Y[p,a,c,t,t+1] = 0;


end;
```

C. Case Study Grocery Distributor/Retailer (Demand and Distances)

Table 40. Pallet demand at the 8 distribution centers (specific for validation and case study)

Distribution Center	Time Period (week)				
	1	2	3	4	5
DC1	10,541	10,843	11,368	10,754	11,539
DC2	2,692	2,824	3,043	2,665	2,918
DC3	5,160	5,264	5,340	5,426	5,153
DC4	2,246	2,436	2,388	1,905	2,340
DC5	2,767	3,296	3,243	3,109	3,236
DC6	2,978	4,396	4,164	4,643	3,542
DC7	4,645	4,954	5,216	4,796	5,281
DC8	2,553	2,527	2,735	2,640	2,754
Total pallet demand at DCs	33,582	36,540	37,497	35,938	36,763

Table 41. Pallet demand at the 75 retailers (specific for validation and case study)

Distribution Center	Time Period (week)				
	1	2	3	4	5
Retailer 1	332	354	308	307	321
Retailer 2	406	432	376	374	392
Retailer 3	470	501	435	434	454
Retailer 4	637	679	590	588	616
Retailer 5	495	528	459	457	479
Retailer 6	556	593	515	513	537
Retailer 7	452	482	419	418	437
Retailer 8	513	547	475	474	496
Retailer 9	310	330	287	286	299
Retailer 10	449	478	415	414	434
Retailer 11	424	452	393	391	410
Retailer 12	555	592	514	513	536
Retailer 13	370	395	343	342	358
Retailer 14	474	505	438	437	458
Retailer 15	497	530	460	459	480
Retailer 16	637	679	590	588	615
Retailer 17	507	540	469	468	490
Retailer 18	461	491	426	425	445
Retailer 19	574	612	532	530	555
Retailer 20	531	566	491	490	513
Retailer 21	519	554	481	479	502
Retailer 22	630	671	583	581	608
Retailer 23	761	811	704	702	735
Retailer 24	377	401	349	348	364
Retailer 25	404	430	374	373	390
Retailer 26	345	367	319	318	333
Retailer 27	487	520	451	450	471
Retailer 28	485	517	449	448	469
Retailer 29	231	247	214	213	223
Retailer 30	249	266	231	230	241
Retailer 31	447	477	414	413	432
Retailer 32	391	417	362	361	378
Retailer 33	397	424	368	367	384
Retailer 34	479	510	443	442	462
Retailer 35	556	593	515	513	537
Retailer 36	337	359	312	311	325
Retailer 37	566	603	524	522	546
Retailer 38	272	290	252	251	263
Retailer 39	385	411	357	356	372
Retailer 40	335	357	310	309	324
Retailer 41	373	398	345	344	360
Retailer 42	716	764	663	661	692
Retailer 43	327	349	303	302	316
Retailer 44	436	465	404	403	422
Retailer 45	360	384	333	332	348
Retailer 46	524	559	485	484	507
Retailer 47	438	467	405	404	423
Retailer 48	535	571	495	494	517
Retailer 49	603	643	558	557	583
Retailer 50	452	482	418	417	436
Retailer 51	378	403	350	349	365
Retailer 52	617	657	571	569	596
Retailer 53	382	407	353	352	369
Retailer 54	394	420	364	363	380
Retailer 55	354	377	328	327	342
Retailer 56	585	624	542	540	566
Retailer 57	421	449	390	389	407
Retailer 58	441	470	408	407	426
Retailer 59	318	339	295	294	307
Retailer 60	392	418	363	362	379
Retailer 61	173	185	161	160	168
Retailer 62	773	824	715	713	746
Retailer 63	326	348	302	301	315
Retailer 64	364	388	337	336	351
Retailer 65	394	420	365	364	381
Retailer 66	368	392	341	340	356
Retailer 67	323	344	299	298	312
Retailer 68	407	433	376	375	393
Retailer 69	481	513	446	444	465
Retailer 70	249	266	231	230	241
Retailer 71	320	341	296	295	309
Retailer 72	402	428	372	371	388
Retailer 73	304	324	282	281	294
Retailer 74	659	703	610	609	637
Retailer 75	790	842	732	729	763
Total pallet demand at RETs	33,682	35,905	31,182	31,089	32,541

Table 42. Percentage of pallet demand from each distribution center to each retailer

	RET1	RET2	RET3	RET4	RET5	RET6	RET7	RET8	RET9	RET10	RET11	RET12	RET13	RET14	RET15
DC1	1.38%	1.73%	2.04%	2.50%	1.91%	2.25%	2.00%	2.23%	1.29%	1.99%	1.70%	2.18%	1.54%	0.79%	1.03%
DC2	1.65%	2.37%	1.93%	3.48%	2.88%	3.32%	2.00%	2.23%	1.61%	1.81%	2.58%	2.98%	1.86%	0.01%	0.01%
DC3	0.96%	1.02%	1.25%	1.85%	1.48%	1.49%	1.24%	1.36%	0.88%	1.18%	1.27%	1.74%	1.16%	1.64%	1.49%
DC4	1.23%	1.35%	1.81%	2.01%	1.40%	1.72%	1.22%	1.68%	1.11%	1.58%	1.22%	1.90%	1.18%	1.33%	1.13%
DC5	1.07%	1.14%	1.31%	2.07%	1.43%	1.59%	1.52%	1.57%	0.86%	1.33%	1.37%	1.62%	1.18%	1.65%	1.33%
DC6	0.87%	1.07%	1.52%	1.97%	1.67%	1.62%	1.41%	1.70%	0.89%	1.44%	1.10%	1.63%	0.84%	1.25%	1.33%
DC7	0.17%	0.26%	0.34%	0.40%	0.35%	0.41%	0.28%	0.35%	0.19%	0.33%	0.19%	0.33%	0.28%	1.95%	2.63%
DC8	0.02%	0.02%	0.02%	0.06%	0.05%	0.04%	0.02%	0.04%	0.01%	0.01%	0.04%	0.05%	0.01%	3.69%	3.40%

	RET16	RET17	RET18	RET19	RET20	RET21	RET22	RET23	RET24	RET25	RET26	RET27	RET28	RET29	RET30
DC1	1.35%	0.94%	0.71%	1.03%	1.05%	0.90%	1.24%	1.43%	0.68%	0.71%	0.61%	0.96%	1.93%	0.97%	1.16%
DC2	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	2.56%	0.95%	1.01%
DC3	1.98%	1.42%	1.40%	1.70%	1.56%	1.71%	2.14%	2.50%	1.39%	1.37%	1.31%	1.65%	1.36%	0.62%	0.63%
DC4	1.69%	1.20%	0.96%	1.34%	1.51%	1.31%	1.36%	1.71%	1.11%	1.00%	0.81%	1.52%	1.49%	0.74%	0.93%
DC5	2.01%	1.43%	1.37%	1.74%	1.56%	1.81%	2.20%	2.41%	1.17%	1.30%	1.09%	1.43%	1.43%	0.59%	0.61%
DC6	1.28%	1.32%	1.48%	1.66%	1.32%	1.43%	1.99%	2.41%	0.89%	1.20%	0.71%	1.23%	1.77%	1.06%	0.74%
DC7	2.97%	3.08%	2.26%	2.98%	2.46%	2.26%	2.29%	2.90%	1.73%	1.91%	1.50%	2.32%	0.31%	0.14%	0.19%
DC8	4.67%	3.38%	3.88%	4.23%	4.08%	3.98%	4.78%	6.19%	2.54%	2.79%	2.69%	3.13%	0.03%	0.01%	0.01%

	RET31	RET32	RET33	RET34	RET35	RET36	RET37	RET38	RET39	RET40	RET41	RET42	RET43	RET44	RET45
DC1	1.77%	1.79%	1.53%	1.92%	2.10%	1.34%	2.21%	1.08%	1.62%	1.50%	1.58%	2.30%	1.48%	1.83%	1.55%
DC2	2.52%	1.82%	2.22%	2.52%	3.44%	1.82%	3.19%	1.46%	1.76%	1.43%	1.57%	5.50%	1.24%	1.94%	1.76%
DC3	1.30%	1.03%	1.10%	1.38%	1.63%	0.97%	1.61%	0.80%	1.02%	0.84%	1.03%	2.27%	0.83%	1.20%	0.96%
DC4	1.33%	1.24%	1.32%	1.56%	1.60%	1.05%	1.80%	0.93%	1.30%	1.19%	1.28%	1.59%	1.14%	1.42%	1.21%
DC5	1.23%	1.05%	1.03%	1.47%	1.57%	0.98%	1.77%	0.77%	1.10%	0.76%	1.05%	2.23%	0.78%	1.28%	0.99%
DC6	1.53%	1.05%	1.53%	1.43%	1.92%	1.13%	1.80%	0.81%	1.42%	1.15%	1.31%	2.66%	1.19%	1.56%	1.09%
DC7	0.30%	0.30%	0.27%	0.36%	0.34%	0.23%	0.35%	0.21%	0.27%	0.31%	0.29%	0.39%	0.31%	0.34%	0.26%
DC8	0.04%	0.02%	0.05%	0.04%	0.05%	0.02%	0.06%	0.03%	0.02%	0.02%	0.02%	0.14%	0.01%	0.03%	0.02%

	RET46	RET47	RET48	RET49	RET50	RET51	RET52	RET53	RET54	RET55	RET56	RET57	RET58	RET59	RET60
DC1	2.11%	1.75%	2.29%	1.25%	0.87%	0.65%	1.27%	0.75%	0.76%	0.76%	1.19%	0.78%	0.83%	0.57%	0.79%
DC2	2.88%	2.20%	2.52%	0.01%	0.01%	0.02%	0.00%	0.01%	0.01%	0.01%	0.02%	0.01%	0.01%	0.01%	1.81%
DC3	1.52%	1.23%	1.54%	1.88%	1.60%	1.30%	2.06%	1.08%	1.14%	1.00%	1.76%	1.25%	1.43%	1.03%	1.12%
DC4	1.59%	1.48%	1.67%	1.60%	1.07%	1.11%	1.66%	0.94%	1.22%	0.98%	1.58%	1.05%	1.09%	0.75%	1.35%
DC5	1.57%	1.17%	1.58%	1.92%	1.48%	1.13%	1.75%	1.15%	1.02%	0.92%	1.71%	1.25%	1.27%	0.99%	1.10%
DC6	1.59%	1.58%	1.54%	1.27%	0.88%	1.10%	1.75%	1.04%	1.02%	1.16%	1.68%	1.12%	1.28%	0.88%	1.25%
DC7	0.37%	0.33%	0.41%	3.06%	2.24%	1.72%	2.99%	2.12%	2.32%	2.03%	2.94%	2.41%	2.57%	1.53%	2.28%
DC8	0.03%	0.03%	0.04%	4.04%	3.12%	2.68%	3.82%	2.53%	2.41%	1.87%	3.78%	2.76%	2.48%	2.35%	0.02%

	RET61	RET62	RET63	RET64	RET65	RET66	RET67	RET68	RET69	RET70	RET71	RET72	RET73	RET74	RET75
DC1	0.45%	1.56%	0.71%	0.78%	0.79%	0.74%	0.68%	1.83%	1.04%	1.07%	1.40%	0.81%	0.58%	1.32%	1.77%
DC2	0.47%	5.06%	1.39%	1.60%	1.75%	1.91%	1.32%	1.97%	2.47%	1.19%	1.67%	0.01%	0.01%	0.02%	0.03%
DC3	0.46%	2.45%	0.93%	1.03%	1.09%	1.08%	0.90%	1.13%	1.33%	0.74%	0.91%	1.08%	0.91%	1.96%	2.34%
DC4	0.75%	1.97%	1.05%	1.39%	1.43%	1.23%	1.22%	1.31%	1.54%	1.05%	0.98%	1.29%	1.12%	1.72%	2.28%
DC5	0.34%	2.58%	0.93%	1.05%	1.11%	1.13%	0.91%	1.06%	1.59%	0.76%	0.90%	1.05%	0.94%	2.01%	2.33%
DC6	0.46%	2.50%	1.00%	1.02%	1.32%	0.97%	0.94%	1.06%	1.46%	0.41%	0.79%	1.33%	0.76%	2.44%	2.06%
DC7	1.14%	3.18%	1.91%	2.06%	2.30%	2.06%	1.95%	0.28%	2.46%	0.18%	0.20%	2.25%	1.77%	2.51%	4.13%
DC8	0.00%	0.10%	0.02%	0.02%	0.02%	0.02%	0.01%	0.02%	0.04%	0.01%	0.02%	2.30%	1.55%	4.99%	4.49%

Table 43. Distances (in miles) between distributor's facilities (specific for validation and case study)

RET	Disribution Center								RC
	DC1	DC2	DC3	DC4	DC5	DC6	DC7	DC8	
1	168.0	168.0	167.0	167.0	173.0	171.0	302.0	302.0	169.0
2	159.0	159.0	158.0	158.0	165.0	163.0	303.0	303.0	161.0
3	63.1	63.1	61.9	61.9	68.4	66.7	258.0	258.0	64.9
4	66.4	66.4	65.3	65.3	71.8	70.1	270.0	270.0	66.5
5	61.5	61.5	60.3	60.3	66.8	65.1	260.0	260.0	63.3
6	73.6	73.6	72.4	72.4	78.9	77.2	271.0	271.0	75.4
7	67.9	67.9	66.7	66.7	73.2	71.5	271.0	271.0	69.7
8	62.0	62.0	60.8	60.8	67.3	65.6	256.0	256.0	63.8
9	137.0	137.0	158.0	158.0	171.0	166.0	239.0	239.0	139.0
10	70.0	70.0	68.8	68.8	75.3	73.6	266.0	266.0	71.8
11	60.6	60.6	59.4	59.4	65.9	64.2	260.0	260.0	62.4
12	68.8	68.8	67.7	67.7	74.2	72.5	272.0	272.0	70.6
13	80.9	80.9	79.7	79.7	86.2	84.5	284.0	284.0	79.3
14	364.0	364.0	365.0	365.0	363.0	353.0	124.0	124.0	358.0
15	377.0	377.0	378.0	378.0	377.0	367.0	159.0	159.0	371.0
16	359.0	359.0	360.0	360.0	359.0	348.0	115.0	115.0	348.0
17	351.0	351.0	352.0	352.0	350.0	340.0	132.0	132.0	343.0
18	351.0	351.0	353.0	353.0	351.0	341.0	130.0	130.0	361.0
19	262.0	262.0	263.0	263.0	261.0	257.0	147.0	147.0	258.0
20	329.0	329.0	330.0	330.0	329.0	318.0	108.0	108.0	312.0
21	367.0	367.0	369.0	369.0	367.0	362.0	163.0	163.0	360.0
22	321.0	321.0	322.0	322.0	321.0	316.0	116.0	116.0	314.0
23	383.0	383.0	384.0	384.0	383.0	378.0	178.0	178.0	377.0
24	424.0	424.0	425.0	425.0	424.0	419.0	231.0	231.0	417.0
25	382.0	382.0	383.0	383.0	381.0	377.0	177.0	177.0	375.0
26	359.0	359.0	360.0	360.0	358.0	354.0	154.0	154.0	351.0
27	312.0	312.0	311.0	311.0	310.0	309.0	153.0	153.0	308.0
28	15.2	15.2	16.6	16.6	15.0	10.4	269.0	269.0	12.9
29	14.4	14.4	15.8	15.8	14.2	6.3	260.0	260.0	8.1
30	36.6	36.6	38.0	38.0	36.4	26.7	243.0	243.0	28.2
31	35.6	35.6	37.0	37.0	35.5	25.3	237.0	237.0	29.7
32	3.6	3.6	4.1	4.1	5.1	8.9	240.0	240.0	7.4
33	10.2	10.2	11.6	11.6	10.0	5.4	264.0	264.0	7.8
34	8.1	8.1	9.5	9.5	7.9	2.8	232.0	232.0	2.3
35	17.5	17.5	18.9	18.9	17.3	7.5	260.0	260.0	9.1
36	8.9	8.9	10.3	10.3	4.6	2.9	231.0	231.0	1.1
37	15.9	15.9	17.2	17.2	15.7	11.1	264.0	264.0	13.5
38	52.4	52.4	53.8	53.8	52.2	42.1	224.0	224.0	43.0
39	7.8	7.8	8.2	8.2	9.3	13.1	244.0	244.0	11.6
40	14.7	14.7	16.1	16.1	14.5	9.9	269.0	269.0	12.4
41	9.1	9.1	9.6	9.6	106.0	14.4	245.0	245.0	12.9
42	8.7	8.7	10.1	10.1	8.5	3.9	238.0	238.0	6.4
43	9.9	9.9	10.4	10.4	11.4	15.2	246.0	246.0	13.7
44	11.2	11.2	11.7	11.7	12.7	16.5	248.0	248.0	15.0
45	17.3	17.3	15.7	15.7	18.8	22.6	254.0	254.0	21.1
46	19.8	19.8	21.2	21.2	19.6	15.0	274.0	274.0	17.5
47	11.5	11.5	11.9	11.9	13.0	12.5	271.0	271.0	15.0
48	3.9	3.9	2.6	2.6	4.9	14.0	245.0	245.0	7.9
49	343.0	343.0	345.0	345.0	343.0	333.0	104.0	104.0	321.0
50	234.0	234.0	235.0	235.0	233.0	230.0	58.7	58.7	325.0
51	266.0	266.0	267.0	267.0	266.0	261.0	63.5	63.5	259.0
52	354.0	354.0	355.0	355.0	354.0	344.0	97.3	97.3	324.0
53	155.0	155.0	156.0	156.0	154.0	150.0	62.4	62.4	224.0
54	243.0	243.0	244.0	244.0	243.0	232.0	51.3	51.3	236.0
55	174.0	174.0	176.0	176.0	174.0	170.0	64.1	64.1	201.0
56	293.0	293.0	295.0	295.0	293.0	283.0	53.5	53.5	288.0
57	283.0	283.0	284.0	284.0	283.0	272.0	70.3	70.3	277.0
58	291.0	291.0	293.0	293.0	291.0	281.0	62.8	62.8	285.0
59	237.0	237.0	238.0	238.0	236.0	232.0	112.0	112.0	227.0
60	88.3	88.3	89.7	89.7	88.1	78.0	210.0	210.0	82.4
61	92.8	92.8	94.2	94.2	92.7	82.5	203.0	203.0	86.9
62	98.5	98.5	99.9	99.9	98.3	88.2	204.0	204.0	92.6
63	93.1	93.1	94.5	94.5	93.0	82.8	202.0	202.0	87.1
64	94.0	94.0	95.4	95.4	93.9	83.7	210.0	210.0	88.1
65	89.8	89.8	91.2	91.2	89.7	79.5	208.0	208.0	84.0
66	92.4	92.4	93.8	93.8	92.3	82.1	216.0	216.0	94.5
67	95.1	95.1	96.4	96.4	94.9	84.7	205.0	205.0	89.2
68	68.8	68.8	70.2	70.2	68.6	58.5	205.0	205.0	62.9
69	90.1	90.1	91.5	91.5	90.0	79.8	205.0	205.0	84.2
70	70.0	70.0	71.4	71.4	69.8	65.1	176.0	176.0	63.3
71	30.2	30.2	31.6	31.6	30.1	25.4	208.0	208.0	23.5
72	101.0	101.0	102.0	102.0	101.0	95.9	143.0	143.0	94.0
73	119.0	119.0	121.0	121.0	119.0	114.0	186.0	186.0	113.0
74	94.4	94.4	95.8	95.8	94.2	84.1	177.0	177.0	90.0
75	169.0	169.0	171.0	171.0	169.0	159.0	133.0	133.0	163.0

D. RESULTS

1. MINIMIZING SYSTEM ENVIRONMENTAL IMPACTS SUBJECT TO MINIMUM SYSTEM COST

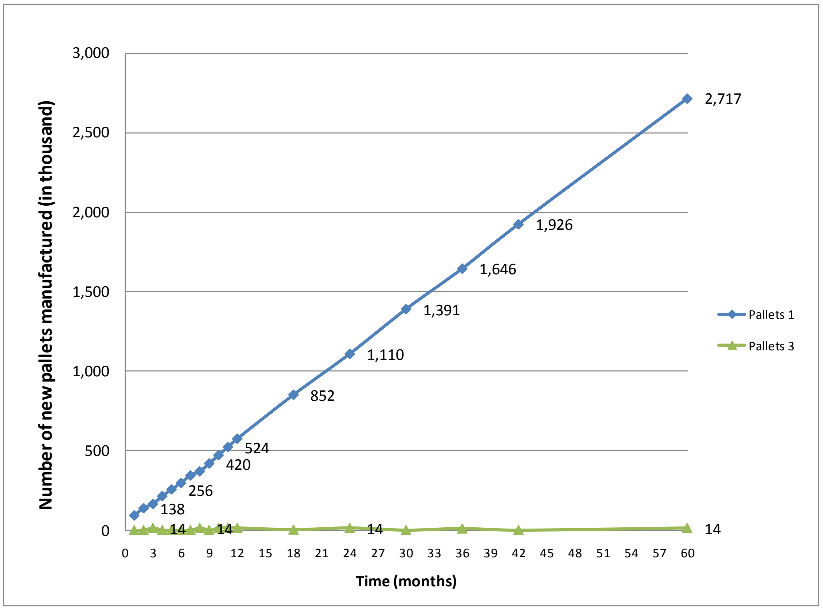

Figure 28. Number of new pallets manufactured per pallet type when minimizing system environmental impacts subject to minimum cost

2. TRADEOFF BETWEEN SYSTEM COSTS AND ENVIRONMENTAL COSTS

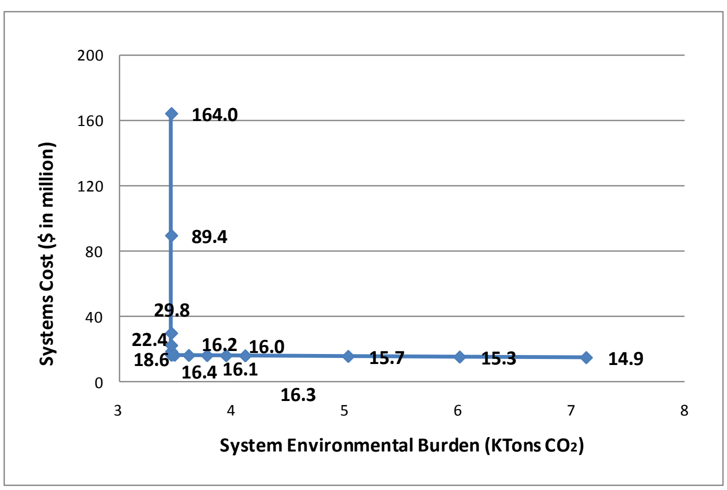

Figure 29. Tradeoff between environmental impacts and costs (Time horizon: 6 months)

3. Analysis of Factors: Pallet Weight and Pallet Purchase/Leasing Cost

Table 44. 64 combinations for factors analysis (factors: Pallet Weight and Purchase/Leasing Cost)

	Weight			Purchase/Leasing Cost		
Runs	**P1**	**P3**	**P4**	**P1**	**P3**	**P4**
1	40	45	40	3	4	5
2	40	45	40	3	4	7
3	40	45	40	3	7	5
4	40	45	40	3	7	7
5	40	45	40	9	4	5
6	40	45	40	9	4	7
7	40	45	40	9	7	5
8	40	45	40	9	7	7
9	40	45	65	3	4	5
10	40	45	65	3	4	7
11	40	45	65	3	7	5
12	40	45	65	3	7	7
13	40	45	65	9	4	5
14	40	45	65	9	4	7
15	40	45	65	9	7	5
16	40	45	65	9	7	7
17	40	75	40	3	4	5
18	40	75	40	3	4	7
19	40	75	40	3	7	5
20	40	75	40	3	7	7
21	40	75	40	9	4	5
22	40	75	40	9	4	7
23	40	75	40	9	7	5
24	40	75	40	9	7	7
25	40	75	65	3	4	5
26	40	75	65	3	4	7
27	40	75	65	3	7	5
28	40	75	65	3	7	7
29	40	75	65	9	4	5
30	40	75	65	9	4	7
31	40	75	65	9	7	5
32	40	75	65	9	7	7
33	65	45	40	3	4	5
34	65	45	40	3	4	7
35	65	45	40	3	7	5
36	65	45	40	3	7	7
37	65	45	40	9	4	5
38	65	45	40	9	4	7
39	65	45	40	9	7	5
40	65	45	40	9	7	7
41	65	45	65	3	4	5
42	65	45	65	3	4	7
43	65	45	65	3	7	5
44	65	45	65	3	7	7
45	65	45	65	9	4	5
46	65	45	65	9	4	7
47	65	45	65	9	7	5
48	65	45	65	9	7	7
49	65	75	40	3	4	5
50	65	75	40	3	4	7
51	65	75	40	3	7	5
52	65	75	40	3	7	7
53	65	75	40	9	4	5
54	65	75	40	9	4	7
55	65	75	40	9	7	5
56	65	75	40	9	7	7
57	65	75	65	3	4	5
58	65	75	65	3	4	7
59	65	75	65	3	7	5
60	65	75	65	3	7	7
61	65	75	65	9	4	5
62	65	75	65	9	4	7
63	65	75	65	9	7	5
64	65	75	65	9	7	7

Table 45. 64 combinations results (Time horizon: 6 months)

min Environmental Costs subject to Costs

Time Horizon: 6 months	Run	System Cost (MM$)	Total Environmental Impact (KTons CO2)	Pallets Manufactured New						Total Pallets Manufactured New
				Pallet 1		Pallet 3		Pallet 4		
α=0	1	$ 14.16	7.0	316,833	100%	-	0%	-	0%	316,833
α=0	2	$ 14.16	7.0	316,833	100%	-	0%	-	0%	316,833
α=0	3	$ 14.16	7.0	316,833	100%	-	0%	-	0%	316,833
α=0	4	$ 14.16	7.0	316,833	100%	-	0%	-	0%	316,833
α=0	5	$ 17.06	3.0	-	0%	113,976	100%	-	0%	113,976
α=0	6	$ 17.06	3.0	-	0%	113,976	100%	-	0%	113,976
α=0	7	$ 17.79	6.6	-	0%	-	0%	108,143	100%	108,143
α=0	8	$ 19.64	6.5	-	0%	-	0%	106,820	100%	106,820
α=0	9	$ 14.16	7.0	316,833	100%	-	0%	-	0%	316,833
α=0	10	$ 14.16	7.0	316,833	100%	-	0%	-	0%	316,833
α=0	11	$ 14.16	7.0	316,833	100%	-	0%	-	0%	316,833
α=0	12	$ 14.16	7.0	316,833	100%	-	0%	-	0%	316,833
α=0	13	$ 17.06	3.0	-	0%	113,976	100%	-	0%	113,976
α=0	14	$ 17.06	3.0	-	0%	113,976	100%	-	0%	113,976
α=0	15	$ 17.79	10.2	-	0%	-	0%	108,143	100%	108,143
α=0	16	$ 19.64	10.1	-	0%	-	0%	106,820	100%	106,820
α=0	17	$ 14.16	7.0	316,833	100%	-	0%	-	0%	316,833
α=0	18	$ 14.16	7.0	316,833	100%	-	0%	-	0%	316,833
α=0	19	$ 14.16	7.0	316,833	100%	-	0%	-	0%	316,833
α=0	20	$ 14.16	7.0	316,833	100%	-	0%	-	0%	316,833
α=0	21	$ 17.06	4.2	-	0%	113,976	100%	-	0%	113,976
α=0	22	$ 17.06	4.2	-	0%	113,976	100%	-	0%	113,976
α=0	23	$ 17.79	6.6	-	0%	-	0%	108,143	100%	108,143
α=0	24	$ 19.64	6.5	-	0%	-	0%	106,820	100%	106,820
α=0	25	$ 14.16	7.0	316,833	100%	-	0%	-	0%	316,833
α=0	26	$ 14.16	7.0	316,833	100%	-	0%	-	0%	316,833
α=0	27	$ 14.16	7.0	316,833	100%	-	0%	-	0%	316,833
α=0	28	$ 14.16	7.0	316,833	100%	-	0%	-	0%	316,833
α=0	29	$ 17.06	4.2	-	0%	113,976	100%	-	0%	113,976
α=0	30	$ 17.06	7.8	-	0%	118,103	100%	-	0%	118,103
α=0	31	$ 17.79	10.2	-	0%	-	0%	108,143	100%	108,143
α=0	32	$ 19.64	10.1	-	0%	-	0%	106,820	100%	106,820
α=0	33	$ 14.16	10.0	316,832	100%	1	0%	-	0%	316,833
α=0	34	$ 14.16	10.0	316,832	100%	1	0%	-	0%	316,833
α=0	35	$ 14.16	10.0	316,833	100%	-	0%	-	0%	316,833
α=0	36	$ 14.16	10.0	316,833	100%	-	0%	-	0%	316,833
α=0	37	$ 17.06	3.3	-	0%	113,976	100%	-	0%	113,976
α=0	38	$ 17.06	3.3	-	0%	113,976	100%	-	0%	113,976
α=0	39	$ 17.79	6.8	-	0%	-	0%	108,143	100%	108,143
α=0	40	$ 19.64	6.8	-	0%	-	0%	106,820	100%	106,820
α=0	41	$ 14.16	10.0	316,832	100%	1	0%	-	0%	316,833
α=0	42	$ 14.16	10.0	316,832	100%	1	0%	-	0%	316,833
α=0	43	$ 14.16	10.0	316,833	100%	-	0%	-	0%	316,833
α=0	44	$ 14.16	10.0	316,833	100%	-	0%	-	0%	316,833
α=0	45	$ 17.06	3.3	-	0%	113,976	100%	-	0%	113,976
α=0	46	$ 17.06	3.3	-	0%	113,976	100%	-	0%	113,976
α=0	47	$ 17.79	10.5	-	0%	-	0%	108,143	100%	108,143
α=0	48	$ 19.64	10.4	-	0%	-	0%	106,820	100%	106,820
α=0	49	$ 14.16	10.0	316,833	100%	-	0%	-	0%	316,833
α=0	50	$ 14.16	10.0	316,833	100%	-	0%	-	0%	316,833
α=0	51	$ 14.16	10.0	316,833	100%	-	0%	-	0%	316,833
α=0	52	$ 14.16	10.0	316,833	100%	-	0%	-	0%	316,833
α=0	53	$ 17.06	4.5	-	0%	113,976	100%	-	0%	113,976
α=0	54	$ 17.06	4.5	-	0%	113,976	100%	-	0%	113,976
α=0	55	$ 17.79	6.8	-	0%	-	0%	108,143	100%	108,143
α=0	56	$ 19.64	6.8	-	0%	-	0%	106,820	100%	106,820
α=0	57	$ 14.16	10.0	316,833	100%	-	0%	-	0%	316,833
α=0	58	$ 14.16	10.0	316,833	100%	-	0%	-	0%	316,833
α=0	59	$ 14.16	10.0	316,833	100%	-	0%	-	0%	316,833
α=0	60	$ 14.16	10.0	316,833	100%	-	0%	-	0%	316,833
α=0	61	$ 17.06	4.5	-	0%	113,976	100%	-	0%	113,976
α=0	62	$ 17.06	4.5	-	0%	113,976	100%	-	0%	113,976
α=0	63	$ 17.79	10.5	-	0%	-	0%	108,143	100%	108,143
α=0	64	$ 19.64	10.4	-	0%	-	0%	106,820	100%	106,820

Table 46. 64 combinations results (Time horizon: 2 years)

min Environmental Costs subject to Costs

Time Horizon: 2 years	Run	System Cost (MM$)	Total Environmental Impact (KTons CO2)	Pallets Manufactured New: Pallet 1		Pallet 3		Pallet 4		Total Pallets Manufactured New
α=0	1	$ 56.27	24.6	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	2	$ 56.27	24.6	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	3	$ 56.27	24.6	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	4	$ 56.27	24.6	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	5	$ 67.70	5.6	-	0%	137,963	100%	-	0%	137,963
α=0	6	$ 67.70	5.6	-	0%	137,963	100%	-	0%	137,963
α=0	7	$ 70.56	9.4	-	0%	-	0%	109,225	100%	109,225
α=0	8	$ 78.09	9.4	-	0%	-	0%	108,630	100%	108,630
α=0	9	$ 56.27	24.6	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	10	$ 56.27	24.6	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	11	$ 56.27	24.6	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	12	$ 56.27	24.6	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	13	$ 67.70	5.6	-	0%	137,963	100%	-	0%	137,963
α=0	14	$ 67.70	5.6	-	0%	137,963	100%	-	0%	137,963
α=0	15	$ 70.56	14.8	-	0%	-	0%	109,225	100%	109,225
α=0	16	$ 78.09	14.7	-	0%	-	0%	108,630	100%	108,630
α=0	17	$ 56.27	24.6	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	18	$ 56.27	24.6	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	19	$ 56.27	24.6	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	20	$ 56.27	24.6	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	21	$ 67.70	8.2	-	0%	137,963	100%	-	0%	137,963
α=0	22	$ 67.70	8.2	-	0%	137,963	100%	-	0%	137,963
α=0	23	$ 70.56	9.4	-	0%	-	0%	109,225	100%	109,225
α=0	24	$ 78.09	9.4	-	0%	-	0%	108,630	100%	108,630
α=0	25	$ 56.27	24.6	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	26	$ 56.27	24.6	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	27	$ 56.27	24.6	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	28	$ 56.27	24.6	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	29	$ 67.70	8.2	-	0%	137,963	100%	-	0%	137,963
α=0	30	$ 67.70	8.2	-	0%	137,963	100%	-	0%	137,963
α=0	31	$ 70.56	14.8	-	0%	-	0%	109,225	100%	109,225
α=0	32	$ 78.09	14.7	-	0%	-	0%	108,630	100%	108,630
α=0	33	$ 56.27	35.2	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	34	$ 56.27	35.2	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	35	$ 56.27	35.2	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	36	$ 56.27	35.2	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	37	$ 67.70	5.8	-	0%	137,963	100%	-	0%	137,963
α=0	38	$ 67.70	5.8	-	0%	137,963	100%	-	0%	137,963
α=0	39	$ 70.56	9.6	-	0%	-	0%	109,225	100%	109,225
α=0	40	$ 78.09	9.6	-	0%	-	0%	108,630	100%	108,630
α=0	41	$ 56.27	35.2	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	42	$ 56.27	35.2	1,125,070	100%	1	0%	-	0%	1,125,071
α=0	43	$ 56.27	35.2	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	44	$ 56.27	35.2	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	45	$ 67.70	5.8	-	0%	137,963	100%	-	0%	137,963
α=0	46	$ 67.70	5.8	-	0%	137,963	100%	-	0%	137,963
α=0	47	$ 70.56	15.0	-	0%	-	0%	109,225	100%	109,225
α=0	48	$ 78.09	15.0	-	0%	-	0%	108,630	100%	108,630
α=0	49	$ 56.27	35.2	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	50	$ 56.27	35.2	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	51	$ 56.27	35.2	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	52	$ 56.27	35.2	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	53	$ 67.70	8.5	-	0%	137,963	100%	-	0%	137,963
α=0	54	$ 67.70	8.5	-	0%	137,963	100%	-	0%	137,963
α=0	55	$ 70.56	9.6	-	0%	-	0%	109,225	100%	109,225
α=0	56	$ 78.09	9.6	-	0%	-	0%	108,630	100%	108,630
α=0	57	$ 56.27	35.2	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	58	$ 56.27	35.2	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	59	$ 56.27	35.2	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	60	$ 56.27	35.2	1,125,070	100%	-	0%	-	0%	1,125,070
α=0	61	$ 67.70	8.5	-	0%	137,963	100%	-	0%	137,963
α=0	62	$ 67.70	8.5	-	0%	137,963	100%	-	0%	137,963
α=0	63	$ 70.56	15.0	-	0%	-	0%	109,225	100%	109,225
α=0	64	$ 78.09	15.0	-	0%	-	0%	108,630	100%	108,630

Table 47. Minimizing environmental impacts subject to minimum system cost (Time horizon: 6 months)

Rate of Cost Increase	Run	System Cost (in million)	System Environmental Cost (KTons CO2)	Pallets Manufactured New						Total Pallets Manufactured New
				Pallet 1		Pallet 3		Pallet 4		
α = 0	1	$ 14.16	7.0	316,833	100%	-	0%	-	0%	316,833
α = 0	5	$ 17.06	3.0	-	0%	113,976	100%	-	0%	113,976
α = 0	7	$ 17.79	6.6	-	0%	-	0%	108,143	100%	108,143

Table 48. Minimizing environmental impacts allowing costs to increase by 20 percent the minimum cost (Time horizon: 6 months)

Rate of Cost Increase	Run	Maximum System Cost Allowed (in million)	System Environmental Cost (KTons CO2)	Pallets Manufactured New						Total Pallets Manufactured New
				Pallet 1		Pallet 3		Pallet 4		
α = 20%	1	$ 16.99	2.9	-	0%	100,407	100%	-	0%	100,407
α = 20%	5	$ 20.48	2.9	-	0%	100,407	100%	-	0%	100,407
α = 20%	7	$ 21.35	2.9	-	0%	100,407	100%	-	0%	100,407

Table 49. Minimizing system cost subject to minimum environmental impacts (Time horizon: 6 months)

Rate of Cost Increase	Run	System Cost (in million)	System Environmental Cost (KTons CO2)	Pallets Manufactured New						Total Pallets Manufactured New
				Pallet 1		Pallet 3		Pallet 4		
α = 0	1	$ 16.63	2.9	-	0%	100,407	100%	-	0%	100,407
α = 0	5	$ 17.29	2.9	-	0%	100,407	100%	-	0%	100,407
α = 0	7	$ 19.93	2.9	-	0%	100,407	100%	-	0%	100,407

Table 50. Minimizing system cost allowing environmental impacts to increase by 20 percent the minimum environmental cost (Time horizon: 6 months)

Rate of Cost Increase	Run	System Cost (in million)	Maximum System Environmental Cost Allowed	Pallets Manufactured New						Total Pallets Manufactured New
				Pallet 1		Pallet 3		Pallet 4		
α = 20%	1	$ 16.19	3.4	46,210	35%	83,970	65%	-	0%	130,180
α = 20%	5	$ 17.06	3.4	-	0%	114,611	100%	-	0%	114,611
α = 20%	7	$ 19.47	3.4	-	0%	86,337	84%	16,019	16%	102,356

4. Analysis of Factors: Pallet Weight and CO_2 footprint from Material, primary production.

Table 51. 9 combinations for factors analysis (factors: Pallet Weight and CO_2 footprint from material production)

Runs	PALLET 1		PALELT 3		PALLET 4		
	Weight	Material CO2 footprint (wood)	Weight	Material CO2 footprint (wood)	Weight	Material CO2 footprint	
						Plastic	Steel
1	45	0.4495	65	0.4495	20	0.86	0.70
2	45	0.4495	65	0.4495	20	2.05	2.05
3	45	0.4495	65	0.4495	20	2.05	2.49
4	45	0.4495	65	0.4495	35	0.86	0.70
5	45	0.4495	65	0.4495	35	2.05	2.05
6	45	0.4495	65	0.4495	35	2.05	2.49
7	45	0.4495	65	0.4495	47.5	0.86	0.70
8	45	0.4495	65	0.4495	47.5	2.05	2.05
9	45	0.4495	65	0.4495	47.5	2.05	2.49

Table 52. 9 combinations results when minimizing system cost subject to minimum environmental impacts (Time horizon: 6 months)

Rate of Cost Increase	Scenario or Run	System Cost (in million)	Total Environmental Impact (KTons CO2)	Pallets Manufactured New						Total Pallets
				Pallet 1		Pallet 3		Pallet 4		
α=0	1	$ 18.15	2.2	-	0%	-	0%	96,263	100%	**96,263**
α=0	2	$ 18.10	3.3	-	0%	25,382	26%	71,904	74%	**97,286**
α=0	3	$ 18.08	3.3	-	0%	34,482	35%	63,169	65%	**97,651**
α=0	4	$ 18.13	3.4	-	0%	9,564	10%	87,070	90%	**96,634**
α=0	5	$ 17.93	3.6	-	0%	100,407	100%	-	0%	**100,407**
α=0	6	$ 17.93	3.6	-	0%	100,407	100%	-	0%	**100,407**
α=0	7	$ 17.93	3.6	-	0%	100,407	100%	-	0%	**100,407**
α=0	8	$ 17.93	3.6	-	0%	100,407	100%	-	0%	**100,407**
α=0	9	$ 17.93	3.6	-	0%	100,407	100%	-	0%	**100,407**

Table 53. 9 combinations results when minimizing system cost subject to environmental impacts for α=5 percent (Time horizon: 6 months)

Rate of Cost Increase	Scenario or Run	System Cost (in million)	Total Environmental Impact (KTons CO2)	Pallets Manufactured New						Total Pallets
				Pallet 1		Pallet 3		Pallet 4		
α = 5%	1	$ 5.18	2.4	-	0%	9,512	10%	87,964	90%	**97,476**
α = 5%	2	$ 7.58	3.4	-	0%	77,296	77%	22,787	23%	**100,083**
α = 5%	3	$ 7.70	3.5	-	0%	82,813	83%	17,541	17%	**100,354**
α = 5%	4	$ 7.88	3.6	-	0%	85,994	86%	14,516	14%	**100,510**
α = 5%	5	$ 8.41	3.8	13,920	13%	95,634	87%	-	0%	**109,554**
α = 5%	6	$ 8.41	3.8	13,920	13%	95,634	87%	-	0%	**109,554**
α = 5%	7	$ 8.41	3.8	13,920	13%	95,634	87%	-	0%	**109,554**
α = 5%	8	$ 8.41	3.8	13,920	13%	95,634	87%	-	0%	**109,554**
α = 5%	9	$ 8.41	3.8	13,920	13%	95,634	87%	-	0%	**109,554**

5. Analysis of Factor: Demand

Table 54. Low demand at DCs

Dc: Pallet Demand at Distribution Centers	Time Period (week)				
	1	2	3	4	5
Sum of total pallet demand	23,508	25,580	26,251	25,161	25,739

Table 55. Low demand at RETs

Db: Pallet Demand at Retailers	Time Period (week)				
	1	2	3	4	5
Sum of total pallet demand	23,577	25,133	21,827	21,762	22,779

Table 56. High demand at DCs

Dc: Pallet Demand at Distribution Centers	Time Period (week)				
	1	2	3	4	5
Sum of total pallet demand	671,641	730,802	749,943	718,764	735,265

Table 57. High demand at RETs

Db: Pallet Demand at Retailers	Time Period (week)				
	1	2	3	4	5
Sum of total pallet demand	673,638	718,098	623,642	621,778	650,820

6. Analysis of Factor: Transportation

Table 58. Distance traveled within distributor's facilities (on average 30 miles)

RET	Disribution Center								RC
	DC1	DC2	DC3	DC4	DC5	DC6	DC7	DC8	
1	16.8	16.8	16.7	16.7	17.3	17.1	30.2	30.2	16.9
2	15.9	15.9	15.8	15.8	16.5	16.3	30.3	30.3	16.1
3	6.3	6.3	6.2	6.2	6.8	6.7	25.8	25.8	6.5
4	6.6	6.6	6.5	6.5	7.2	7.0	27.0	27.0	6.7
5	6.2	6.2	6.0	6.0	6.7	6.5	26.0	26.0	6.3
6	7.4	7.4	7.2	7.2	7.9	7.7	27.1	27.1	7.5
7	6.8	6.8	6.7	6.7	7.3	7.2	27.1	27.1	7.0
8	6.2	6.2	6.1	6.1	6.7	6.6	25.6	25.6	6.4
9	13.7	13.7	15.8	15.8	17.1	16.6	23.9	23.9	13.9
10	7.0	7.0	6.9	6.9	7.5	7.4	26.6	26.6	7.2
11	6.1	6.1	5.9	5.9	6.6	6.4	26.0	26.0	6.2
12	6.9	6.9	6.8	6.8	7.4	7.3	27.2	27.2	7.1
13	8.1	8.1	8.0	8.0	8.6	8.5	28.4	28.4	7.9
14	36.4	36.4	36.5	36.5	36.3	35.3	12.4	12.4	35.8
15	37.7	37.7	37.8	37.8	37.7	36.7	15.9	15.9	37.1
16	35.9	35.9	36.0	36.0	35.9	34.8	11.5	11.5	34.8
17	35.1	35.1	35.2	35.2	35.0	34.0	13.2	13.2	34.3
18	35.1	35.1	35.3	35.3	35.1	34.1	13.0	13.0	36.1
19	26.2	26.2	26.3	26.3	26.1	25.7	14.7	14.7	25.8
20	32.9	32.9	33.0	33.0	32.9	31.8	10.8	10.8	31.2
21	36.7	36.7	36.9	36.9	36.7	36.2	16.3	16.3	36.0
22	32.1	32.1	32.2	32.2	32.1	31.6	11.6	11.6	31.4
23	38.3	38.3	38.4	38.4	38.3	37.8	17.8	17.8	37.7
24	42.4	42.4	42.5	42.5	42.4	41.9	23.1	23.1	41.7
25	38.2	38.2	38.3	38.3	38.1	37.7	17.7	17.7	37.5
26	35.9	35.9	36.0	36.0	35.8	35.4	15.4	15.4	35.1
27	31.2	31.2	31.1	31.1	31.0	30.9	15.3	15.3	30.8
28	1.5	1.5	1.7	1.7	1.5	1.0	26.9	26.9	1.3
29	1.4	1.4	1.6	1.6	1.4	0.6	26.0	26.0	0.8
30	3.7	3.7	3.8	3.8	3.6	2.7	24.3	24.3	2.8
31	3.6	3.6	3.7	3.7	3.6	2.5	23.7	23.7	3.0
32	0.4	0.4	0.4	0.4	0.5	0.9	24.0	24.0	0.7
33	1.0	1.0	1.2	1.2	1.0	0.5	26.4	26.4	0.8
34	0.8	0.8	1.0	1.0	0.8	0.3	23.2	23.2	0.2
35	1.8	1.8	1.9	1.9	1.7	0.8	26.0	26.0	0.9
36	0.9	0.9	1.0	1.0	0.5	0.3	23.1	23.1	0.1
37	1.6	1.6	1.7	1.7	1.6	1.1	26.4	26.4	1.4
38	5.2	5.2	5.4	5.4	5.2	4.2	22.4	22.4	4.3
39	0.8	0.8	0.8	0.8	0.9	1.3	24.4	24.4	1.2
40	1.5	1.5	1.6	1.6	1.5	1.0	26.9	26.9	1.2
41	0.9	0.9	1.0	1.0	10.6	1.4	24.5	24.5	1.3
42	0.9	0.9	1.0	1.0	0.9	0.4	23.8	23.8	0.6
43	1.0	1.0	1.0	1.0	1.1	1.5	24.6	24.6	1.4
44	1.1	1.1	1.2	1.2	1.3	1.7	24.8	24.8	1.5
45	1.7	1.7	1.6	1.6	1.9	2.3	25.4	25.4	2.1
46	2.0	2.0	2.1	2.1	2.0	1.5	27.4	27.4	1.8
47	1.2	1.2	1.2	1.2	1.3	1.3	27.1	27.1	1.5
48	0.4	0.4	0.3	0.3	0.5	1.4	24.5	24.5	0.8
49	34.3	34.3	34.5	34.5	34.3	33.3	10.4	10.4	32.1
50	23.4	23.4	23.5	23.5	23.3	23.0	5.9	5.9	32.5
51	26.6	26.6	26.7	26.7	26.6	26.1	6.4	6.4	25.9
52	35.4	35.4	35.5	35.5	35.4	34.4	9.7	9.7	32.4
53	15.5	15.5	15.6	15.6	15.4	15.0	6.2	6.2	22.4
54	24.3	24.3	24.4	24.4	24.3	23.2	5.1	5.1	23.6
55	17.4	17.4	17.6	17.6	17.4	17.0	6.4	6.4	20.1
56	29.3	29.3	29.5	29.5	29.3	28.3	5.4	5.4	28.8
57	28.3	28.3	28.4	28.4	28.3	27.2	7.0	7.0	27.7
58	29.1	29.1	29.3	29.3	29.1	28.1	6.3	6.3	28.5
59	23.7	23.7	23.8	23.8	23.6	23.2	11.2	11.2	22.7
60	8.8	8.8	9.0	9.0	8.8	7.8	21.0	21.0	8.2
61	9.3	9.3	9.4	9.4	9.3	8.3	20.3	20.3	8.7
62	9.9	9.9	10.0	10.0	9.8	8.8	20.4	20.4	9.3
63	9.3	9.3	9.5	9.5	9.3	8.3	20.2	20.2	8.7
64	9.4	9.4	9.5	9.5	9.4	8.4	21.0	21.0	8.8
65	9.0	9.0	9.1	9.1	9.0	8.0	20.8	20.8	8.4
66	9.2	9.2	9.4	9.4	9.2	8.2	21.6	21.6	9.5
67	9.5	9.5	9.6	9.6	9.5	8.5	20.5	20.5	8.9
68	6.9	6.9	7.0	7.0	6.9	5.9	20.5	20.5	6.3
69	9.0	9.0	9.2	9.2	9.0	8.0	20.5	20.5	8.4
70	7.0	7.0	7.1	7.1	7.0	6.5	17.6	17.6	6.3
71	3.0	3.0	3.2	3.2	3.0	2.5	20.8	20.8	2.4
72	10.1	10.1	10.2	10.2	10.1	9.6	14.3	14.3	9.4
73	11.9	11.9	12.1	12.1	11.9	11.4	18.6	18.6	11.3
74	9.4	9.4	9.6	9.6	9.4	8.4	17.7	17.7	9.0
75	16.9	16.9	17.1	17.1	16.9	15.9	13.3	13.3	16.3

Table 59. Distance traveled within distributor's facilities (on average 3,000 miles)

RET	Disribution Center								RC
	DC1	DC2	DC3	DC4	DC5	DC6	DC7	DC8	
1	1680.0	1680.0	1670.0	1670.0	1730.0	1710.0	3020.0	3020.0	1690.0
2	1590.0	1590.0	1580.0	1580.0	1650.0	1630.0	3030.0	3030.0	1610.0
3	631.0	631.0	619.0	619.0	684.0	667.0	2580.0	2580.0	649.0
4	664.0	664.0	653.0	653.0	718.0	701.0	2700.0	2700.0	665.0
5	615.0	615.0	603.0	603.0	668.0	651.0	2600.0	2600.0	633.0
6	736.0	736.0	724.0	724.0	789.0	772.0	2710.0	2710.0	754.0
7	679.0	679.0	667.0	667.0	732.0	715.0	2710.0	2710.0	697.0
8	620.0	620.0	608.0	608.0	673.0	656.0	2560.0	2560.0	638.0
9	1370.0	1370.0	1580.0	1580.0	1710.0	1660.0	2390.0	2390.0	1390.0
10	700.0	700.0	688.0	688.0	753.0	736.0	2660.0	2660.0	718.0
11	606.0	606.0	594.0	594.0	659.0	642.0	2600.0	2600.0	624.0
12	688.0	688.0	677.0	677.0	742.0	725.0	2720.0	2720.0	706.0
13	809.0	809.0	797.0	797.0	862.0	845.0	2840.0	2840.0	793.0
14	3640.0	3640.0	3650.0	3650.0	3630.0	3530.0	1240.0	1240.0	3580.0
15	3770.0	3770.0	3780.0	3780.0	3770.0	3670.0	1590.0	1590.0	3710.0
16	3590.0	3590.0	3600.0	3600.0	3590.0	3480.0	1150.0	1150.0	3480.0
17	3510.0	3510.0	3520.0	3520.0	3500.0	3400.0	1320.0	1320.0	3430.0
18	3510.0	3510.0	3530.0	3530.0	3510.0	3410.0	1300.0	1300.0	3610.0
19	2620.0	2620.0	2630.0	2630.0	2610.0	2570.0	1470.0	1470.0	2580.0
20	3290.0	3290.0	3300.0	3300.0	3290.0	3180.0	1080.0	1080.0	3120.0
21	3670.0	3670.0	3690.0	3690.0	3670.0	3620.0	1630.0	1630.0	3600.0
22	3210.0	3210.0	3220.0	3220.0	3210.0	3160.0	1160.0	1160.0	3140.0
23	3830.0	3830.0	3840.0	3840.0	3830.0	3780.0	1780.0	1780.0	3770.0
24	4240.0	4240.0	4250.0	4250.0	4240.0	4190.0	2310.0	2310.0	4170.0
25	3820.0	3820.0	3830.0	3830.0	3810.0	3770.0	1770.0	1770.0	3750.0
26	3590.0	3590.0	3600.0	3600.0	3580.0	3540.0	1540.0	1540.0	3510.0
27	3120.0	3120.0	3110.0	3110.0	3100.0	3090.0	1530.0	1530.0	3080.0
28	152.0	152.0	166.0	166.0	150.0	104.0	2690.0	2690.0	129.0
29	144.0	144.0	158.0	158.0	142.0	63.0	2600.0	2600.0	81.0
30	366.0	366.0	380.0	380.0	364.0	267.0	2430.0	2430.0	282.0
31	356.0	356.0	370.0	370.0	355.0	253.0	2370.0	2370.0	297.0
32	36.0	36.0	41.0	41.0	51.0	89.0	2400.0	2400.0	74.0
33	102.0	102.0	116.0	116.0	100.0	54.0	2640.0	2640.0	78.0
34	81.0	81.0	95.0	95.0	79.0	28.0	2320.0	2320.0	23.0
35	175.0	175.0	189.0	189.0	173.0	75.0	2600.0	2600.0	91.0
36	89.0	89.0	103.0	103.0	46.0	29.0	2310.0	2310.0	11.0
37	159.0	159.0	172.0	172.0	157.0	111.0	2640.0	2640.0	135.0
38	524.0	524.0	538.0	538.0	522.0	421.0	2240.0	2240.0	430.0
39	78.0	78.0	82.0	82.0	93.0	131.0	2440.0	2440.0	116.0
40	147.0	147.0	161.0	161.0	145.0	99.0	2690.0	2690.0	124.0
41	91.0	91.0	96.0	96.0	1060.0	144.0	2450.0	2450.0	129.0
42	87.0	87.0	101.0	101.0	85.0	39.0	2380.0	2380.0	64.0
43	99.0	99.0	104.0	104.0	114.0	152.0	2460.0	2460.0	137.0
44	112.0	112.0	117.0	117.0	127.0	165.0	2480.0	2480.0	150.0
45	173.0	173.0	157.0	157.0	188.0	226.0	2540.0	2540.0	211.0
46	198.0	198.0	212.0	212.0	196.0	150.0	2740.0	2740.0	175.0
47	115.0	115.0	119.0	119.0	130.0	125.0	2710.0	2710.0	150.0
48	39.0	39.0	26.0	26.0	49.0	140.0	2450.0	2450.0	79.0
49	3430.0	3430.0	3450.0	3450.0	3430.0	3330.0	1040.0	1040.0	3210.0
50	2340.0	2340.0	2350.0	2350.0	2330.0	2300.0	587.0	587.0	3250.0
51	2660.0	2660.0	2670.0	2670.0	2660.0	2610.0	635.0	635.0	2590.0
52	3540.0	3540.0	3550.0	3550.0	3540.0	3440.0	973.0	973.0	3240.0
53	1550.0	1550.0	1560.0	1560.0	1540.0	1500.0	624.0	624.0	2240.0
54	2430.0	2430.0	2440.0	2440.0	2430.0	2320.0	513.0	513.0	2360.0
55	1740.0	1740.0	1760.0	1760.0	1740.0	1700.0	641.0	641.0	2010.0
56	2930.0	2930.0	2950.0	2950.0	2930.0	2830.0	535.0	535.0	2880.0
57	2830.0	2830.0	2840.0	2840.0	2830.0	2720.0	703.0	703.0	2770.0
58	2910.0	2910.0	2930.0	2930.0	2910.0	2810.0	628.0	628.0	2850.0
59	2370.0	2370.0	2380.0	2380.0	2360.0	2320.0	1120.0	1120.0	2270.0
60	883.0	883.0	897.0	897.0	881.0	780.0	2100.0	2100.0	824.0
61	928.0	928.0	942.0	942.0	927.0	825.0	2030.0	2030.0	869.0
62	985.0	985.0	999.0	999.0	983.0	882.0	2040.0	2040.0	926.0
63	931.0	931.0	945.0	945.0	930.0	828.0	2020.0	2020.0	871.0
64	940.0	940.0	954.0	954.0	939.0	837.0	2100.0	2100.0	881.0
65	898.0	898.0	912.0	912.0	897.0	795.0	2080.0	2080.0	840.0
66	924.0	924.0	938.0	938.0	923.0	821.0	2160.0	2160.0	945.0
67	951.0	951.0	964.0	964.0	949.0	847.0	2050.0	2050.0	892.0
68	688.0	688.0	702.0	702.0	686.0	585.0	2050.0	2050.0	629.0
69	901.0	901.0	915.0	915.0	900.0	798.0	2050.0	2050.0	842.0
70	700.0	700.0	714.0	714.0	698.0	651.0	1760.0	1760.0	633.0
71	302.0	302.0	316.0	316.0	301.0	254.0	2080.0	2080.0	235.0
72	1010.0	1010.0	1020.0	1020.0	1010.0	959.0	1430.0	1430.0	940.0
73	1190.0	1190.0	1210.0	1210.0	1190.0	1140.0	1860.0	1860.0	1130.0
74	944.0	944.0	958.0	958.0	942.0	841.0	1770.0	1770.0	900.0
75	1690.0	1690.0	1710.0	1710.0	1690.0	1590.0	1330.0	1330.0	1630.0

7. Pallets End-of-Life alternatives Analysis

Table 60. End-of-life alternatives base scenario vs. regulation scenario when minimizing system cost subject to environmental impacts (Time horizon: 2 years)

Base Scenario

Pallet Type	Landfill	Downcycle/Recycle
Pallet 1	1%	89%
Pallet 3	1%	19%
Pallet 4	0%	100%

Scenario Regulation

Pallet Type	Landfill	Downcycle/Recycle
Pallet 1	0%	10%
Pallet 3	0%	10%
Pallet 4	0%	100%

		Base Scenario				Scenario Regulation			
Time Horizon		2 years				2 years			
Pallet Type in the System		Pallet 1	Total % per EOL	Pallet 3	Total % per EOL	Pallet 1	Total % per EOL	Pallet 3	Total % per EOL
Pallet End-of-Life Alternative	Repaired to reuse	2,486	10%	119,218	80%	109,371	90%	122,653	90%
	Recycled to reuse	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Downcycled	22,125	89%	28,315	19%	12,153	10%	13,629	10%
	Landfilled	249	1%	1,491	1%	-	0%	-	0%
	Incinerated	-	0%	-	0%	-	0%	-	0%