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Comparison of Treatment Methods for Pallets Using LCA and Dynamic Programming

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Abstract

Heat treatment and Methyl Bromide fumigation are the two treatment methods used to kill pests in wood packaging materials such as pallets before being used for global trade logistics. With rise in global trade, the use of these treatment methods has increased, and thus increasing costs and emissions of methyl bromide and other greenhouse gases. The proposed methodology comprises of a comparison of treatment methods and a comparison of wooden and plastic type pallet using Life Cycle Analysis (LCA). The implementation combines LCA with dynamic programming to optimize "pallet type" decisions at various stages of the product life cycle.

Keywords
Life Cycle Assessment (LCA); Phytosanitary treatment; Dynamic Programming; Shortest path problem; Pallets;

1. Introduction
Wood packaging materials such as pallets, crates, and dunnage are prone to infestation by pests and hence need to be treated so as to kill the pests before being used for trade and logistics. Pallets before being put into use for packaging and transportation are treated to kill the various pests, fungi and nematode that may be contained in it. Some of these pests are: pinewood nematodes (Bursaphelenchus xylophilis), Asian longhorned beetle (Anoplophora glabripennis), bark beetles (Scolytidae), weevils (Curculionidae), etc. In the past years, according to reports in the literature, approximately 4,500 new species have been introduced into United States [1]. From 1906 to 1991, just 79 of the 4,500 introduced species have caused losses estimated to be at least $97 billion [2]. These species have continued to affect natural systems such as agriculture, forestry, industry and human health. Most common pathways causing introduction of foreign pests are in the form of "unintended by products" of international trade and commerce.

Following the detection of Asian long horned beetle (Anoplophora glabripennis) in New York in 1996, the development of international standards to prevent the spread of pests has been considered with prime interest by Animal and Plant Health Inspection Service (APHIS). Hence treatment of wood packaging materials to kill infested pests, before use in global logistics is of utmost importance and is mandated by the ISPM 15 (International Standard for Phytosanitary Measures). This research focuses on an LCA study to compare the various treatment methods such as Methyl Bromide Fumigation, Heat Treatment, RF Heating and "No treatment"- in this case, plastic pallets. Radio Frequency heating is being proposed by the research team as an alternative treatment method with adequate treatment efficacy.

2. Literature Review

2.1. RF Heating as a Phytosanitary Treatment Method

Increased international trade has led to an increase in need for treatment methods such as heat treatment and methyl bromide fumigation. Increase in Methyl Bromide, a Class I ozone-depleting substance, affects the atmosphere adversely. Similarly, increased use of heat treatment requires energy and increases costs. Moreover, these methods are ineffective for large volume lumbers. Accordingly, significant emphasis is placed on finding an alternative treatment method that is effective, environmentally clean and economically viable.

The use of dielectric heating methods using microwaves was investigated and its efficacy to kill several species of cerambycids has been proved to date [3, 4, 5]. Dielectric heating provides volumetric heating of the wood profile and hence is more energy efficient and faster. Conventional heating heats only the surface of the material, and heats up internal areas using thermal conduction. It has been, however, shown that microwaves cannot effectively penetrate beyond 20cm. RF heating penetrates deeper into the wood profile, thus killing the pests more effectively and consumes less time [6]. RF heating provides differential heating of wood, ensuring that pests are selectively heated while not significantly heating the wood itself [6]. Often microwave heating suffers from "blind spots" as it may not heat every region in the wood profile, however, RF heating does not suffer from this disadvantage [7]. RF heating is faster and uses electrical energy, thus having reduced energy consumption and environmental burdens.

2.2. Life Cycle Analysis (LCA)

The principles and framework included in a life cycle assessment study is described in the International Standard ISO 14040 Environmental management - life cycle assessment - principles and framework; 1997. Life Cycle Assessment (LCA) is an environmental risk analysis tool used in industries to determine the environmental impacts of a product or service throughout its life cycle. It has been used as a framework of comparison across various material, processing, and logistics options. The four stages in a life cycle analysis are: Goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and life cycle interpretation [8].

In the first stage the practitioner defines the goal of the LCA study, functional unit and the boundaries of the product system [9]. Secondly, all consumptions and emissions occurring in a product's life cycle are recorded in the life cycle inventory. Further then, in the LCIA stage, an assessment of the environmental exchanges identified during the data collection stage is done [9]. Life cycle interpretation is the fourth stage in an LCA study wherein results from the LCI and LCIA are quantified, evaluated and communicated effectively [9]. Life cycle interpretation is a process that gives credibility to the results obtained in the previous three phases of the LCA study [10].

Previous studies have shown that LCA's have been conducted for wood products, packaging systems and pallets to analyze their environmental impacts and/or cost benefits [11, 12, 13]. [11] compares the LCA of CHEP pallets against GMA pallets and GMA one way pallets. It was concluded that CHEP pallet systems have the least solid wastes generated, minimum requirement for energy during production and the least global warming potential. [12] consists of an LCA conducted on eight types of pallets to study their performance during the use phase. Pallets with highest performance were proved to be the twin sheet thermoformed HDPE plastic pallets and press wood pallets with the least performance. Performance consideration included number of trips without damage, cost, weight and environmental impacts. [13] consists of an LCA conducted to compare a single use wooden pallet and a plastic packaging system, Enviropak® T760. At a confidence level of 96.5% it was concluded that, the environmental impacts of the wooden pallet system was four times more severe than the Enviropak® T760.

The literature also consists of LCAs conducted on various wood products [14, 15, 16]. [17] consists of an LCA conducted to compare the environmental impacts of three packaging systems namely, wooden and cardboard boxes and plastic crates, throughout their life cycle. According to authors, wooden boxes perform better with respect to primary energy demand, summer smog, ozone depletion and global warming potential. [18] evaluated the environmental impacts of using reed fiber as a substitute for glass fiber in reinforced plastics and their application in plastic transport pallets. The reed pallets showed lesser environmental impacts as compared to glass fiber reinforced pallets.

3. Proposed Methodology

This section presents a methodology to select the best treatment method that minimizes both the cost as well as the carbon footprint incurred throughout the life cycle stages of wood and plastic pallets. Carbon footprint is "the total amount of greenhouse gases emitted during a process". Greenhouse gases are gases in the atmosphere that absorb radiations and emit thermal infra-red radiations back to the earth's surface. The main greenhouse gases contained in the atmosphere of the earth are water vapor, carbon dioxide, methane, nitrous oxide, and ozone. Carbon footprint is often quantified using an indicator known as Global Warming Potential (GWP) which is defined as "the ratio of heat trapped by one unit mass of the greenhouse gas to that of one unit mass of CO2 over a specified time period" (US Environmental Protection Agency).

3.1. Wood Pallets

Wood pallets are manufactured from hardwood/softwood lumber. Lumber is first harvested, sawn, dried and planed to produce lumber necessary for manufacture of pallets. Pallets are then manufactured according to various dimensions. The life span of wood pallets is measured as the number of trips for which it can be used throughout its lifetime and is assumed to be an average of 15 trips [19]. Carbon footprint is calculated for the three treatment methods as well. The carbon footprint of a wood pallet is summarized in Table 1 and Figures 1 and 2. The total carbon footprint for a wood pallet, for one trip is calculated to be 17.13 kg CO_2 eq. The data analysis software used is Simapro v7.1. The carbon footprint for heat treatment is due to the combustion of fuel source (LPG), and heating of the oven. Each pallet uses 1/20th of a gallon and the amount of CO_2 emitted is calculated from this. The carbon footprint for Methyl Bromide fumigation is calculated from the total amount of methyl bromide emitted per usage which is 51-88% of applied dosage [20].

Table 1: Carbon footprint and cost information

Parameter		Wood Pallets Heat Treat / Methyl Br Fumig / RF Heating			Plastic Pallets No Treatment
Number of trips considered		15			15
Number of pallets required		1			1
Carbon Footprint (Kg CO_2 eq.)	Production	7.86			56.2
	Transportation	0.64			1.10
	Treatment	HT 1.39	MB 0.18	RF 0.71	0.00
	End of Life	8.3			5.76
Total Carbon Footprint (kg CO_2)		17.72	16.58	17.10	63.16
Cost Information ($)	Average Cost per pallet	$11.00			$23.50
	Transportation Cost per pallet	$0.45 - $2			$0.45 - $2
	Recycling Cost per pallet	$1.63			$4.90
	Treatment Cost	HT $1.00		MB $1.69	$0
Total Cost ($)		$15.63		$14.93	$29.7

3.2. Plastic Pallets

Plastic pallets are made from plastic and materials such as high density polyethylene (HDPE), polypropylene, etc. by methods such as by Injection Molding, Structural Foam Molding, and Thermoforming. They are easily recyclable, resistant to attack of pests and have longer life spans. Majority of environmental burdens from the plastic pallet are caused during the manufacture of high density polyethylene (HDPE). The total carbon footprint of a plastic pallet for one trip is calculated to be 63.16 kg CO_2 eq. The life of a plastic pallet is modeled as 100 trips [19]. Pallets at the end of their life are broken down and melted for reuse. Carbon footprint and cost information is summarized in Table 1 and Figures 1 and 2.

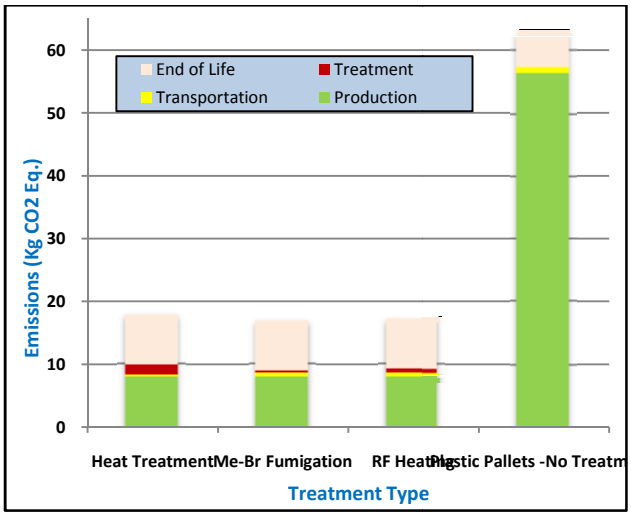

Figure 1: CO_2 emissions (kg) per pallet

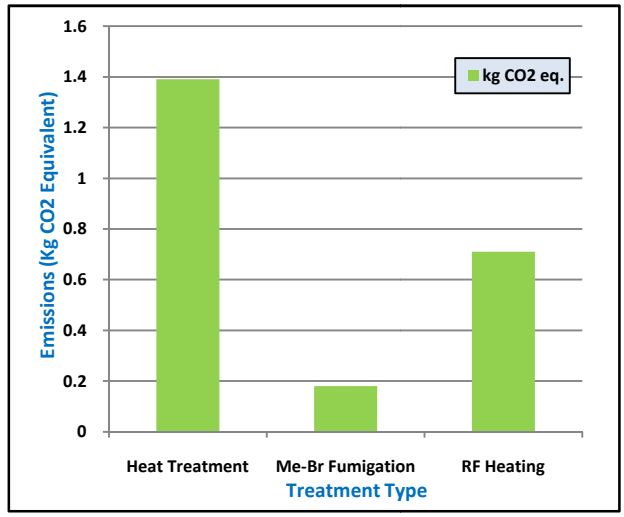

Figure 2: CO_2 emissions (kg) for each treatment

For the minimization problem at hand, the methodology proposed here is an implementation of the shortest path problem, which is a specific case of dynamic programming. In a shortest path problem, the objective is to determine the path with the shortest distance. The shortest path problem is adapted to the treatment selection problem in order to determine the treatment method that incurs the least cost and carbon footprint throughout various life cycle (LC) stages of a pallet. Hence, a multi-stage decision making approach using dynamic programming is applied to the problem as described in the conceptual design problem in [20]. In [20], authors have applied a concept selection approach based on a multi stage decision problem formulation to determine the best configuration of "concepts" to incorporate into a final design. In this study, we use a similar approach to select the best pallet and treatment option where the selection can be made at different life cycle stages.

Table 2: Formulation of the Treatment Selection Problem as a Shortest Path Problem (Adapted from [21]).

	Meaning while solving the shortest path	**Meaning while solving the best treatment synthesis**
Stage	A transition from a city to an adjacent city *(n)*	A transition from a LC stage to the next LC stage *(n)*
State	A city *(n, i)*	A treatment *(n, i)*
Action	Taking a particular route from a city *(k)*	Selecting a particular treatment type or pallet material *(k)*
Return	Distance from a city to an adjacent city *r(n ,i, k)*	Carbon footprint / cost incurred by selecting a treatment *r(n, i, k)*
Optimal value of a state	Distance from the corresponding city to the terminal city under optimal plan *f(n ,i)*	Carbon footprint / cost incurred from a life cycle stage to the final stage under optimal plan *f(n, i)*

where, $f(n,i)$ can be calculated as: $f(n,i) = \underset{k \in K}{Min}\,[r(n,i,k) + f(n-1,t(n,i,k))]$

The four life cycle stages of a pallet considered here are: production, phytosanitary treatment, transportation/use and end of life/recycling. The four treatment scenarios are heat treatment, methyl bromide fumigation, RF heating and "no treatment", in this case, plastic pallets. The life cycle of a pallet formulated in the form of a shortest path problem is illustrated in fig. 3.

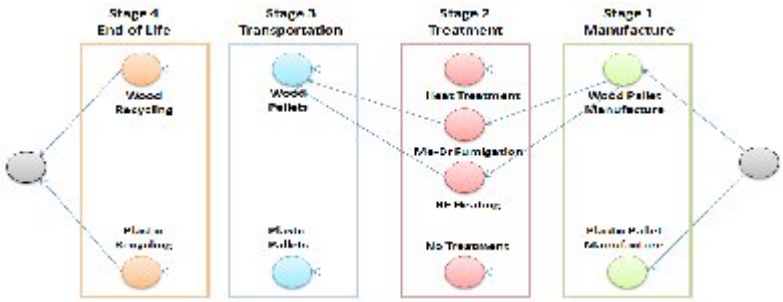

Figure 3: Formulation of the Treatment Selection Problem as a Shortest Path Problem

The dynamic programming model is used to determine the best pallet choice in each life cycle stage using the shortest path algorithm. The calculations to determine the optimal plan is carried out manually. Two scenarios are considered, the amount of carbon footprint and cost incurred for 15 trips and that for 100 trips. As an example, the calculated values for 15 trips is shown in Table 2, values are obtained for 100 trips in a similar manner. Once the cost information and carbon footprint is calculated, these values are used in the nodal diagram shown in figure 3.

The shortest path problem algorithm is then used to determine in each life cycle stage, the option that generates the least cost and carbon footprint (CF). The results obtained for 15 trips are shown in Table 4. Stages 1, 2, 3 and 4 represent production, treatment, transportation and end of life recycling/disposal. Each stage has two states and is shown in figure 3. For example, in stage 3, transportation, the two states are Wood pallets and Plastic pallets.

The most preferable option in each stage is bolded. For 15 trips, it can be seen from Table 3 that, one wooden and plastic pallet is required, with the wooden pallet generating the least amount of footprint and cost (Table 4). It can also be seen that, at the end of production, treatment and transportation, wood pallets are more preferable than their counterparts, in terms of cumulative costs and carbon footprint caused. Results are obtained similarly for the case of 100 trips as well.

With respect to carbon footprint and cost, for the 15 trips case, wood pallets are more preferable during all life cycle stages, unlike the 100 trips case, where except for production, plastic pallets are more cost efficient and green in all stages.

Table 3: Carbon Footprint and Cost

Parameter		Wood Pallets			Plastic Pallets
		Heat Treat/ Me-Br Fumig/ RF Heating			No Treatment
Number of trips considered				15	15
Number of pallets required				1	1
Carbon Footprint (Kg CO_2 eq.)	Production			7.86	56.3
	Transportation			0.61	1.10
	Treatment	HT 1.59	MB 0.18	RF 0.71	0.00
	End of Life			8.3	5.76
Total Carbon Footprint (kg CO_2)		17.72	16.55	17.11	63.16
Cost Information ($)	Average Cost per pallet			$11.00	$23.50
	Transportation Cost per pallet			$0.45 $7	$0.45 $3
	Recycling Cost per pallet			$1.63	$1.90
	Treatment Cost	HT $1.00	MB $1.69		$0
Total Cost ($)		$15.63	$14.93		$29.7

Table 4: Shortest path problem formulation results

Carbon Footprint					Cost					
Stage	State	Action	Value (kg CO_2 eq)	Best Option	Stage	State	Action	Value ($)		Best Option
1	1	1	7.86	Wood	1	1	1	11.00		Wood
1	2	1	56.3		1	2	1	23.50		
2	1	1	7.86 + 1.59 = 9.45		2	1	1	1.00 + 11.00 = 12.00		Wood
2	2	1	7.86 + 0.18 = 8.04	Wood	2	2	1	1.69 + 11.00 = 12.69		
2	3	1	7.86 + 0.71 = 8.57		No cost information for RF Heating					
2	4	1	56.3 + 0.0 = 56.3		2	4	1	0.00 + 23.50 = 23.50		
3	1	1	0.61 + 9.45 = 9.09		3	1	1	1.30 + 12.00 = 13.30		Wood
3	1	2	0.64 + 8.04 = 8.68	Wood	3	1	2	1.30 + 12.69 = 13.99		
3	1	3	0.64 + 8.57 = 9.21		3	1	1	1.30 + 23.50 = 24.80		
3	2	1	1.10 + 56.3 = 57.40							
4	1	1	8.3 + 8.68 = 16.98	Wood	4	1	1	1.63 + 13.30 = 14.93		Wood
4	2	1	5.67 + 57.40 = 63.07		4	2	1	4.90 + 24.80 = 29.70		

5. Results

The results are summarized in Table 5, where three factors, namely: number of pallets required, cost incurred and carbon footprint are presented. Number of pallets required is defined as the number of wooden and plastic pallets required for a particular number of trips. The cost factor includes cost of production, transportation, treatment and end of life recycling/disposal. Similarly, the carbon footprint factor includes the environmental burden created

during production, transportation, treatment and end of life activities. To determine the total cost associated with each pallet and number of trips, the cost equivalent of carbon footprint is determined using the Social Cost of Carbon (SCC). SCC is defined as the cost incurred due to the emission of one unit of carbon dioxide. For calculations, the mean peer reviewed value of \$12/tCO_2 or \$0.012/kg CO_2 from the 2007 IPCC report is used.

Table 5: Summary of Results

Trips	Number of Pallets required		Cost (\$)		Carbon Footprint (kg CO_2 eq.)		Social Cost of Carbon (per kg CO_2)	Total Cost Equivalent	
	Wood	Plastic	Wood	Plastic	Wood	Plastic		Wood	Plastic
15 trips	1	1	\$14.93	\$29.70	17.13	63.16	\$0.012	\$15.54	\$30.93
100 trips	7	1	\$96.71	\$29.70	122.57	63.16	\$0.012	\$100.99	\$30.93

For 15 trips, it was determined that, wood pallets incur the least amount of carbon footprint and costs throughout their entire life cycle. However, for 100 trips, it was seen that plastic pallets are more cost efficient and cause least environmental burden. This was due to the fact that manufacture of just one plastic pallet was required as opposed to seven wooden pallets needed for 100 trips. It can be seen that, determining the best pallet in terms of costs and environmental burden varies with respect to the number of trips considered. As shown in Table 5, for 15 trips, wood pallets have a lesser impact and cost, whereas for 100 trips, plastic pallets are a better option.

6. Conclusions

This paper presents an overview of how life cycle analysis and dynamic programming can be combined to help with providing optimized solutions for each stage in a product's life cycle. While comparing the treatment methods, it must be noted that though MeBr fumigation has a lesser carbon footprint value, it has a very high ozone depletion potential of 0.51, thus making RF heating a much better treatment option. For simplicity, while only limited options are considered here, incorporation of an optimization tool makes a much larger scale problem solvable with efficiency. Overall, the results point to the importance of use span estimation (15 vs. 100 trips) as a critical determinant of optimized solutions. As such our team is currently working on multi-objective optimization algorithms that account for estimated useful life.

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