An Environmental and Economic Evaluation of Construction & Demolition Waste based Wood-Composite Pallets and Virgin Wood Pallets

Elizabeth Ellen Ernst

Thesis of 60 ECTS credits
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Abstract

Construction and demolition waste (CDW) is one of the most voluminous waste streams generated in the European Union. By 2020, the goal of the Waste Framework Directive 200/98/EC is to have EU the member states recover 70% of the total waste volume. Looking for ways to utilize recovered CDW as feedstock for raw material is a critical method for achieving the EU waste targets. This thesis looks the possibility of using CDW to produce wood-plastic composite (WPC) pallets from and environmental and economic perspective and compares them to pallets made from virgin wood material.

A life cycle approach was used to evaluate the environmental impacts of both pallet systems. The global warming potential (GWP) was evaluated and the results found that for 1000 pallet trips the WPC pallet has a lower impact on the GWP. Economically, the cost/benefit of providing a WPC or wood pallet was evaluated from the perspective of a pallet pooling company. Three cost variables were taken into account; the cost of pallet acquisition, repair, and theft management. For 1000 pallet trips the WPC proved to be less costly for the pallet pooling company. The results were due largely to the number of pallets it takes to fulfill the functional unit of 1000 pallet trips; 12 wood pallets and 7 WPC. In every life cycle stage, other than the use phase, the wooden pallet had a lower environmental impact when counting biogenic carbon as a net emission of zero. Further research into pallet cost and LCA impact categories is recommended and encouraged.

Umhverfis- og hagfræðilegt mat á vörubrettum sem annars vegar eru endurunnin úr úrgangi niðurrifs og bygginga og hins vegar úr hráum við.

Elizabeth Ernst

júní 2019

Útdráttur

Úrgangur niðurrifs og bygginga (ÚNB) er eitt fyrirferðamesta úrgangsstreymi Evrópusambandsins. Fyrir árið 2020 er markmið Úrgangstilskipunnar 200/98/EC að fá Evrópusambandsríki til að endurheimta 70% þessa úrgangsmagns. Að finna leiðir til að nýta þennan endurheimta ÚNB í endurunnin hráefni er mikilvægt til að uppfylla úrgangsmarkmið Evrópusambandsins. Ritgerð þessi skoðar möguleika þess að nota ÚNB í framleiðslu vörubretta úr plast- og viðarblöndu (PVB) bæði frá umhverfismiðuðu og hagfræðilegu sjónarhorni auk þess að bera saman vörubretti framleidd úr, annars vegar PVB og hins vegar hráum við.

Líftími vörubrettanna spilaði lykilhlutverk í umhverfismiðuðu mati á báðum gerðum vörubretta. Lagt var mat á hnatthlýnunarmátt (HHM) og niðurstöðurnar bentu til þess að að PVB vörubrettin höfðu minni áhrif á HHM. Hagfræðilega, var lagt á mat kostað og hagnað framleiðslu á PVB vörubrettum og viðar vörumbrettum út frá sjónarhorni vörubretta-leigufyrirtækis. Þriggja kostnaðarbreyta var tekið tillit til; hversu mikið það kostar að eignast vörubretti, viðgerðir og þjófnaðarstjórnun. Fyrir 1000 vörubretta-ferðir reyndust PVB vörubrettin vera ódýrari valmöguleikinn fyrir fyrirtækið. Þetta er vegna þess að PVB vörubrettin eru hagnýtari en þau sem gerð eru úr viði, fyrir 1000 vörubretta-ferðir þarf 7 PVB vörubretti en 12 viðar vörubretti. Mælt er með og hvatt er til áframhaldandi rannsókna á kostnaði vörubretta og á mati líftíma mismunandi vörubretta.

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I dedicate this thesis to Alex Voightman, without whom I never would have had the courage to fly.

Acknowledgements

"'The thing about growing up with Fred and George,' said Ginny thoughtfully, 'is that you sort of start thinking anything's possible if you've got enough nerve.' " —*Harry Potter and the Half-Blood Prince*

This thesis project has been a formative experience. The challenges faced on an academic and personal level have led to level of growth that I did not know was possible. None of this would have happened without the tribe of people around me offering their support and wisdom.

I would first and foremost like to thank my parents and my sister for their never-ending love and encouragement. As well as my Icelandic family of fellow MSc students who I have gotten to grow with these past two years. I would especially like to thank Kaisa Grönman, Miia Liikanen, Jouni Havukainen, and Heli Kasurinen for making me feel welcome in a new country and for their guidance throughout this process. I would like to acknowledge Tuire Tapanen as the completion of my first draft would not have happened without her generous hospitality. Thank you to Ivan Deviatkin, and Kaisa again, for all of their help during the editing process as well as my supervisors Mika Horttanainen and Juliet Newson for their time and instruction.

I would also like to thank the Erasmus + internship program for funding my time in Finland as my time spent working at LUT was invaluable. I would like to acknowledge Dan Dillion for allowing me to interview him about the pallet lifecycle and Ásdís Sól Ágústsdóttir for her help translating the abstract to Icelandic.

Preface

This dissertation is original work by the author, Elizabeth Ernst.

Contents

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List of Abbreviations

ADPE	Abiotic Resource Depletion Potential
CDW	Construction and Demolition Waste
CAGR	Compound Annual Growth Rate
CBA	Cost-Benefit Analysis
CE	Circular Economy
CSR	Corporate Social Responsibility
EC	European Commission
EIA	Environmental Impact Assessment
EIRR	Economic Internal Rate of Return
EoL	End of Life
EU	European Union
GHG	Green House Gas
GWP	Global Warming Potential
HDPE	High-Density Polyethylene
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organization
LCA	Life Cycle Analysis
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDPE	Low Density Polyethylene
MAPP	Maleated polypropylene
MODP	Multi Objective Decision Programming
NVP	Net Present Value
PE	Polyethylene
PMMA	Polymethyl methacrylate
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinylchloride
RFID	Radio Frequency Identification
SETAC	Society of Environmental Toxicology and Chemistry
TOC	Total Organic Waste Content
UNEP	United Nations Environment Program
UV	Ultraviolet
WPC	Wood Plastic Composite
WtE	Waste to Energy

Chapter 1

Introduction

As the doomsday clock ticks ever closer to midnight, global threats of terrorism and resource strain due to mass migration, pale in comparison to the ominous and omnipresent threat of global warming. Looking across the bleak landscape of the 21st century, the question of what to do with the voluminous waste generated by humanity's day to day living seems to echo across nations. In answer, those, blessed or cursed, with the responsibility of leadership seem to approach the situation head on through innovation and policy, or alternatively, choose to stick their heads firmly in the sand while the world burns around them.

The policies and directives of the European Union (EU), without arguing their actual effectiveness, strive to push Europe towards a future of social responsibility and environmental stewardship. It is in the absurdity of the day, where concerned scientists and climate change deniers are given the same amount of air time on the news, that this thesis is written, and hopes to offer something to the scientific community.

According to the European Commission (EC), construction and demolition waste (CDW) is one of the largest and most voluminous waste streams generated in the EU. They have made it a goal of the Waste Framework Directive 200/98/EC [1] to have the member states recycle 70% of their CDW by the year 2020. However, as of 2017 the majority of member states only recover or recycle up to 50% of the CDW they generate. The following research concerns itself with the repurposing of CDW in Finland as a feedstock for wood plastic composite (WPC) pallets.

This thesis is framed in the context of the circular economy (CE) and the 21st century global concern of how to keep systems and products circulating at their highest levels. The Ellen Macarthur Foundation [2], a non-profit company spearheading the CE movement, defines the circular economy as a gradual "*decoupling of economic activity from the consumption of finite resources, and designing waste out of the system. Underpinned by a transition to renewable energy resources, the circular model builds economic, natural, and social capital. It is based on these three principles: designing out waste and pollution, keeping products and materials in use, and regenerating natural systems*." As shown in Figure 1, the CE aims to transition the global socio-economic machine from a linear economy, or one that moves from raw material extraction to disposal without any material recovery, to an economy that aims to reduce resource extraction by circulating material in "loops".

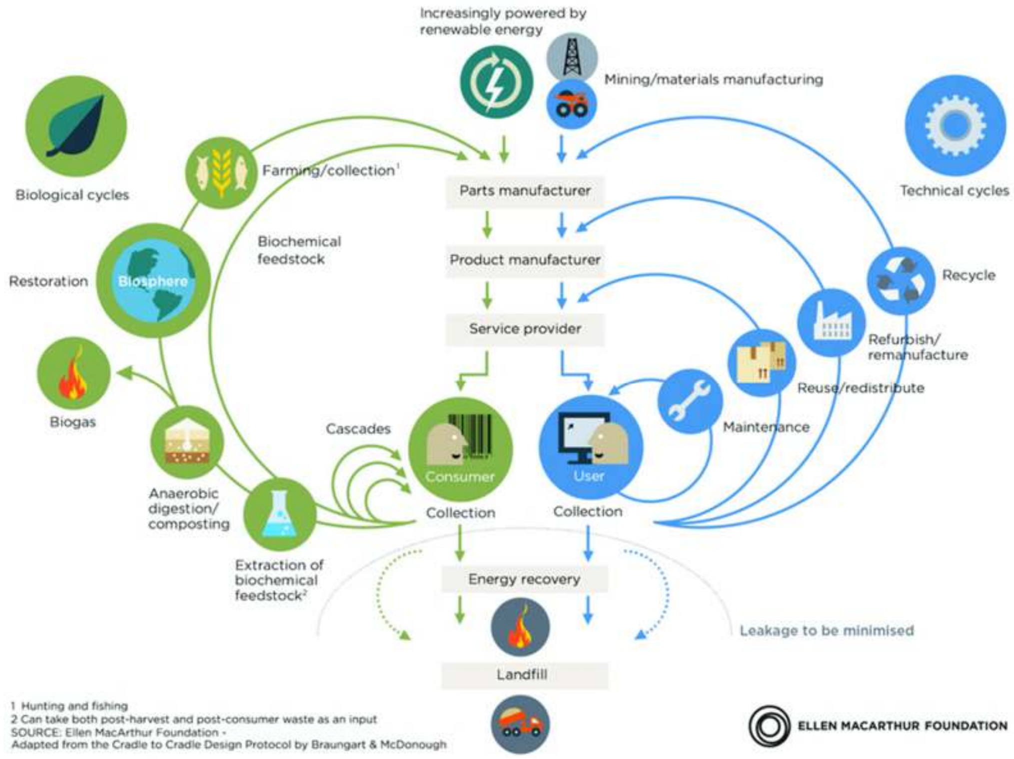

Figure 1. An infographic representing the CE. It illustrates the continuous flow of technical and biological materials thought the 'value circle' [2].

A transition to a CE has to occur on many levels. From product design, that utilizes waste as a new feedstock for materials, to individual patterns of consumption. Shifting from chasing after new shiny i phones, for example, to buying goods that can be repaired and/or are made to last. However, both changes would be almost impossible without a subsequent change in business strategies and societal demand.

In a similar vein to the Ellen MacArthur foundation, the European Commission adopted the waste hierarchy in 2008 in Directive 2008/98/EC [3] (see Figure 2). The inverted pyramid shows the most desirable scenario at the top, which is waste prevention, and ends with waste disposal on the bottom. The disposal category includes landfilling, whereas recovery includes waste incineration with energy recovery. This thesis is concerned with latter two stages of the waste hierarchy.

Figure 2. Waste hierarchy that shows the most preferable option at the top, prevention, to the least preferable waste management option, disposal [1].

Looking at waste as a potential raw material feedstock for new products helps "to close the loops," so to speak. While remanufacturing is one of the larger loops in Figure 1 (the smaller the have a higher resource efficiency), it still can be a better use of waste than, for instance, incineration or landfilling. This project looks at the potential of using CDW waste as a feedstock for WPC and aims to environmentally and economically compare them to pallets manufactured from virgin wood.

The EC stated in their Road map to a Resource Efficient Europe [4] that if waste is to reused as a raw material, then recycling and reuse need to be given a higher priority. In order to accomplish this and create a CE, a combination of policies would need to be enacted. These would range from implementing a life cycle approach in product design, creating an appropriate regulatory framework, investment in modern facilities for waste treatment, and a better waste collection process [9].

1.1 CIRCWASTE

While this thesis is not officially associated with the CIRCWASTE project in Finland[1], the topic and subsequent research of this thesis was inspired by this project. Specifically, the processing plant in South Karelia which is working on producing products made from construction and demolition waste. CIRCWASTE is a seven-year EU LIFE IP [5] project consisting of 19 sub-projects carried out by five separate Finnish regions with the aim of creating a more circular economy The total cost of the project was reported to be 2,000,000 euros, of which the European Regional Development Fund supplied 45%. The project focuses on material flow, resource management, and the prevention of waste [6]. It is the government's goal to have Finland become a leading circular nation by 2025. According to conservative estimates, the CE is expected to generate 2 to 3 billion euros of added value potential in Finland's national economy by 2030. In order to accomplish this, researchers and businesses are focusing on 5 inter-woven service areas;

1.A sustainable food system
2. Forest based loops
3. Technological loops
4. Transport and logistics
5. Joint action [3]

According to Sitra, the Finnish Innovation Fund [7], "*the goal for Finland is to build its competitiveness by means of sustainable material use ... by minimizing the need for virgin raw materials and maximizing the length of the material product loops, as well as utilizing opportunities for reuse. The same applies to the design of products manufactured by secondary materials.* It is through this paradigm that the CIRCWASTE project was contrived, each of the pilot projects addresses one or more of the five interwoven service areas listed above. The participating Finnish region of South Karelia is currently engaged in a pilot research project on CDW derived composite products. The pilot plant collects CDW from the surrounding area and uses it to produce new composite products. Its capacity is around 2000-3000 tonnes per year and the majority of the raw material feedstock is sourced from mixed recycled plastics and wood fibers [5] .

1.2 Bioeconomy

The circular economy and bioeconomy are entwined concepts. The bioeconomy is defined as "*an economy where renewable biomasses are produced and converted into value added materials, chemicals, food, feeds, fuels, and energy: therefore, it represents a valid, reliable way to achieve equitable, sustainable, post carbon-societies*." [8] The idea of

[1] http://www.materiaalitkiertoon.fi/en-US

creating economic value from renewable biomass can be shown on the left side of Figure 1. The circular economy places important emphasis on sustainably sourcing energy production and the recovery of biochemical feedstock. Transitioning to sustainably managed bioeconomy would mean the de-fossilization of major industries. For instance, wood and its derivative composite products can be used as a substitution for non-renewable building materials like concrete and steel [9]. Not all activities occurring under the umbrella of the bioeconomy are sustainable. Forests, for instance, can be utilized faster than they can recover and many marine resources are well past overburdened. In the EU strategy for the development of the Baltic sea region [10], reaching a united strategy for all relevant stakeholders to sustainably manage bioeconomic resources was emphasized. In order to achieve this, five development principles were identified [10]:

- Sustainable resource management for responsible use
- Food security and health for all
- Resilient and diverse ecosystems for a thriving planet
- Inclusive economic and social prosperity
- Sustainable Consumption

While the majority of the five principles listed above are well beyond the scope of this thesis, sustainable resource management is highly relevant. The principles further elaborate that sustainable resource management means [10] "*upgrading residues and waste to higher products and services to optimize the quality and the value of the bio-mass* and *to contribute to the circular bio-solutions that reuse and recycle materials throughout the value chain*." Utilizing CDW to create WPC pallets not only upcycles waste into a new product but it is also a bio solution that capitalizes on the recycling of wood. Using waste material to create new products increases the resource efficiency, which is a common aim of both the circular economy and a sustainable bio economy.

As the bioeconomy grows, there is concern that there will not be enough wood from sustainably managed sources to meet market demand by 2030 [11]. By cascading the biomass and extending its life into another cycle or product, wood resources can be used more efficiently. WPC can substitute virgin wood products which can make it a more resource friendly material.

1.3 Construction and Demolition Waste

As stated in the introduction, the EU has made it a goal for its member states to recycle at least 70% of their CDW by 2020. Not all of the reported CDW waste from the member states can be taken prima facie. Countries like Finland include [12]. "*naturally occurring materials excavated in the course of construction activities that do not have a utilization plan*" in their CDW in waste statistics. This means, soils that meet a certain minimum contamination threshold are included in the national CDW stats. The result being that the majority of CDW generated in Finland are soils. Other EU members states exclude soils completely from their reported CDW fractions, which makes it challenging to compare national CDW waste statistics.

That being said, a report was completed in 2017 for the EC [13] on the current CDW waste generation in the 28 member states and listed potential areas for improvement. Figure 3 shows the amount of CDW generated per member state in 2012. The larger member states generate more CDW. According to Figure 3, Finland ranks in the top 7 members states for most voluminous generation of CDW. However, due to the inclusion of soils in CDW fractions, Finland's ranking among the member states may, in actuality, be lower.

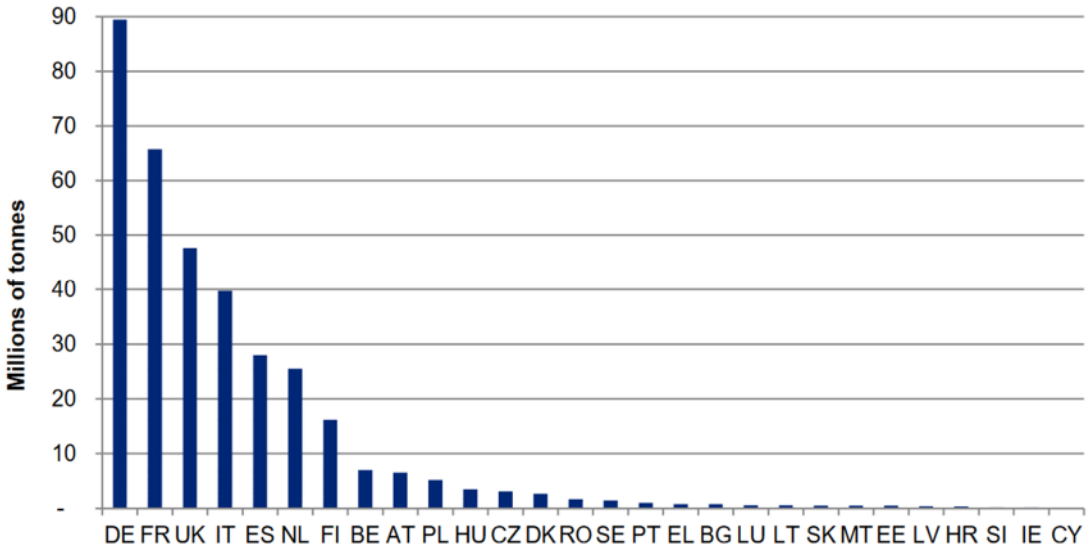

Figure 3. M tonnes of CDW Generated in 2012 by the EU 28 [13].

The report also listed the distance each member state was from the 2020 CDW recovery target (70%). As shown in Figure 4, only 22 of the 28 EU states self-reported their CDW recovery rates from 2010-2012. For the years 2010 and 2011, Finland reported a roughly 37% distance to the EU target.

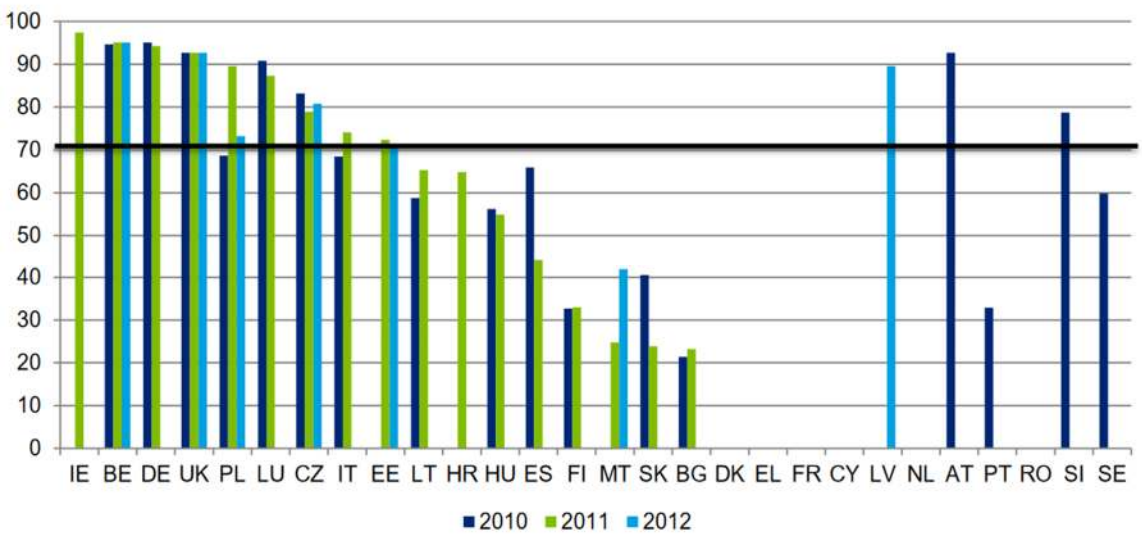

Figure 4. Distance to 2020 target (%) per member state in reference period 2010-2012. Only 22 of the 38 member states reported CDW recovery statistics.

1.3.1 CDW Management in Finland

Finland defines construction and demolition waste as [12] "*waste from new construction, repairs and demolition of buildings and other fixed structures, civil engineering work, or other corresponding construction*." Table 1 shows the CDW generation in Finland for the years 2011 and 2012. It is taken from a report on construction and demolition waste management in Finland [12]. Of the non-hazardous CDW totals reported, the majority is made up of soil, reported as an estimated 16 tonnes in 2011 and 14 tonnes in 2012. The total CDW waste generation decreased from the year 2011 to 2012.

As of the date of this report [12], 2015, there was no published data about the treatment wood waste solely from CDW, only information regarding the treatment of wood waste from all sectors in summation.

Table 1. Officially reported CDW generation data from Finland 2011-2012[12].

Waste Category	Quantity Generated in 2011 (Million Tonnes)	Quantity Generated in 2012 (Million Tonnes)
Non-Hazardous CDW	18.1	15.9
-CDW from Buildings	1.7	1.5-2
-Soil	16 (estimated)	14 (estimated)
Hazardous CDW	0.33	0.15
Total CDW	18.4	16.0

The taxes imposed on landfilling, and further associated costs, promote the recycling of CDW. The landfill taxes on CDW actually created a new market for processed reclaimed concrete. The Government Decree on Waste (179/2012) [14] "*requires the organization of separate collection, and recovery of waste generated in refurbishment, demolition, and new construction, which has led to efficient recycling of separate waste streams*." This decree also outlines the minimum CDW fractions requirement for collection and recovery. They are as follows:

- Concrete, brick, mineral tile, ceramic waste
- Gypsum based waste
- Non-impregnated wood waste
- Metal waste
- Glass waste
- Plastic waste
- Paper and cardboard waste
- Soil waste and rock material

The Government Decree on Landfills (331/2013) [15] has established a limit value on organic waste fractions. The maximum permissible amount (after 2020), measured as TOC (total organic carbon) or LOI (loss of ignition content), is 10%. Until 2020 15% of the total waste fraction can be organic content.

Several challenges to CDW recovery in Finland include the sheer size of the country. CDW, in some cases, has to be transported vast distances to recovery plants which complicates the recovery process and increases the emission profile of recovery. Furthermore, product standards and regulations have not been adapted to account for the unique characteristics of CDW which discourages its use as a new material feedstock. A report by the Finnish Ministry of the Environment [16] identified that the demand for recovered wood waste was impacted by the abundant availability of clean wood. CDW is often impure or contaminated which can make recovery difficult.

A study [17] was conducted in 2015 on how current practices in CDW management matched with the goal of recycling 70% of CDW by 2020. Material and energy recovery rates were assessed, along with the climate change impacts, environmental life cycle costing, and applicability of the best available technology. They found that while Finland's overall system was already economically profitable and produced environmental benefits, it would not achieve the EU's waste directive benchmark by 2020. With regards to the wood fraction of CDW, the majority of it is recovered as energy. If wood continues to have a large share of Finland's CDW fraction, then material recovery would need to supplement energy recovery. Better source separation and finding other uses for contaminated wood was listed as a suggested solution. Utilizing CDW for WPC production will aid Finland in reaching the 70% material recovery rate.

1.4 Wood Plastic Composites

The term WPC refers to wood-based fibers, or flour; such as lumber, natural fibers, and vainer, that are mixed with plastic polymers (usually polypropylene (PP) or polyethylene (PE)) and other additives to form a composite material. Compounds such as coupling agents, light stabilizers, and lubricants can be added to the mixture, as well as additives that help overcome wood's hydrophilic and plastic's hydrophobic tendencies. Without such additives, the incompatibility of wood and plastic can lead to a reduction in tensile strength [18].The use of WPC in an industrial capacity began more than a century ago. Wood-flour was combined with phenol formaldehyde resin to create a gear shifting knob made of composite material [19]. Today, WPC is mostly used in the construction and automotive industries.

Figure 5 shows that WPC was mainly used for decking in 2012. This is due its resistance to biological degradation, making WPC more suitable for outdoor utilization than timber or untreated wood [20]. Some of the other advantages of WPC include: a high durability, an acceptable relative strength and stiffness comparted to virgin wood and plastic, and a lighter weight than conventional wood.

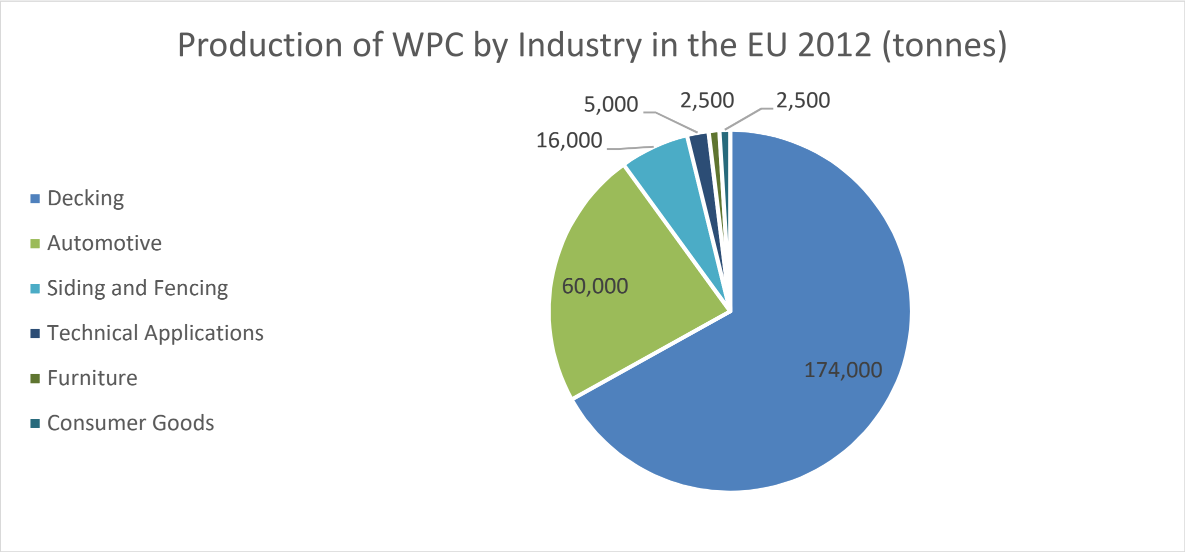

Figure 5. Production of WPC in the EU 2012 separated by industry use (in tonnes).

1.4.1 Production of WPC

The three most common methods of WPC manufacturing are via extrusion, injection molding, or compression molding (also referred to as pressing). The former method producing linear boards that can be cut and fastened into products like pallets, and the latter two producing a molded 3-D shape. Figure 6 illustrates the production pathways that WPC can take though the production process. The raw material can either be extruded directly, or go through a compounding step (also called agglomeration). Once compounded, the material can enter the injection molding, extrusion, or compression molding process. The path the WPC material takes depends on the equipment and goals of the WPC producers.

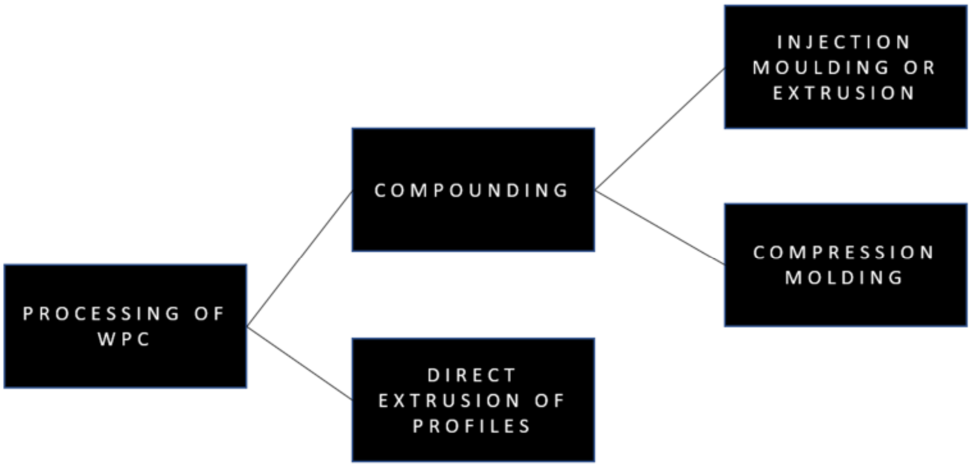

Figure 6. Manufacturing Process Tree for WPC [19].

The WPC manufacturer can choose from three different wood sources when producing the composite, wood chips, wood flour, or wood fibers from the refiner. If they come from virgin sources, they are by-products of native coniferous wood harvesting or from saw mills [21]. The most common plastic polymers blended with the wood fibers are PE, PP, polyvinyl chloride (PVC), polystyrene (PS), and poly methyl methacrylate (PMMA). These polymers are the most employed for WPC production due their availably and the thermal resistivity of the wood fibers [21].

The wood fibers will start to degrade at 220°C [19], thus a polymer with a lower melt temperature needs to be employed. There are a litany of additives that can be mixed with the polymer and wood fibers. Most commonly employed are lubricants, coupling agents, fillers, biocides, dies, light stabilizers, smoke suppressants, and flame retardants. Each additive strengthens or improves some aspect of the WPC material, from blocking degradation from UV light to preventing pests from nesting [22].

Before the raw materials are passed through an injection mold or extrusion line, there are several processing steps that they may need to go through. Polymers may need to be pelletized or the wood fibers may need to pass through a crusher or hammermill to break them into smaller pieces. The raw materials are then heated and blended together in a process called agglomeration [22]. This results in a homogenous mixture that is then ready to be further processed in an injection mold or extruder. As the model for the WPC in this thesis is based on extrusion, the rest of the discussion of WPC production will limit itself to the extrusion production process [22].

The job of the extrusion machine is to melt the plastic and compound (mix) wood, plastics or polymers, and additives [19]. There are four main types of extrusion systems used to produce WPC;

1. Single screw
2. Co-rotating twin screw
3. Counter-rotating twin screw and
4. Woodtruder

The advantages and disadvantages of each process are shown in Table 2.

Table 2-The four main extrusion processing lines and their respective advantages and disadvantages [19].

Type of Extruder	Process	Advantages	Disadvantages
Single Screw	**Two Stages**: Mixing and melting **Material Preparation**: Pre-compounded fiber filled polymer pellets **Material Feed:** Gravity Hopper **Mixing/Melting Mechanism:** Barrel Heat and Screw Shear	-Proven Technology -Lowest Capitol Cost	-High Material cost -Lower Output rates -Drying system requires -High screw speed -Greater risk of thermal decomposition -Cannot keep melt temperatures low
Co-Rotating Twin Screw	**Mechanism**: Co-rotating twin screw coupled with a "hot melt" singe extruder **Material Preparation**: None **Material Feed:** Gravimetric feeders/ twin screw side feeders **Mixing/Melting Mechanism:** Barrel Heat and screw speed, screw mixing	-Can process wood with a higher moisture content as the extruder is used to dry the mixture	-Need for peripheral feeding systems -Greater risk of burning the WPC blend due to a lack of screw cooling system -High melt temperature
Counter Rotating Twin Screw	**Mechanism**: Parallel or conical screw configurations **Material Preparation**: Fiber drying with high intensity blending **Material Feed:** Crammer feeder **Mixing/Melting Mechanism:** Barrel Heat and screw speed, screw mixing	-Low screw speed and low sheer mixing -Proven technology	-Drying system required -Size reduction system for fed materials may be necessary -Pre-blending system required -Transportation of raw materials may impact the ratio of the pre-blended raw materials
Woodtruder	**Mechanism**: Parallel co-rotating screws and 75mm single screw extruder. Polymers are melted separately from the wood fiber **Material Preparation**: None **Material Feed:** Gravimetric feeders **Mixing/Melting Mechanism:** Barrel Heat and screw mixing	-Fibers do not burn as the plastic is melted separately -Able to process wood at ambient moisture content -Low melt temperature at high pressure	-High capital costs -Using the primary extrusion process as a drying mechanism is not efficient

Each type of extrusion machine comes with a trade-off. The WoodTruder is able to process wood and plastic at a low melt temperature and high pressure which reduces damage to the composite blend. However, the resulting capital costs are high compared to the single screw and counter screw options. The single screw extrusion machine has a low capital cost but requires much more upfront processing of the raw materials before they are ready to be processed [19].

One the type of extrusion line is selected; the extrusion die must be considered. The die controls the shape and size of the extruded pieces and they range in complexity based on the desired profile. Once the extruded material passes through the die, a cooling tank is used to freeze the material into a linear shape. Then, linear profile can then be sawed or fastened into end products like pallets or decking boards. [19].

In terms of the recipe blends for WPC, the ratio of wood to plastic in European WPC is on average found to be 70:30 [23]. The ratio of wood to plastic in the material varies greatly and the share of plastic and filler can range 30-70% [21]. As the wood fraction increases so does the impact strength, modulus values, and flexural strength, while the tensile strength, melt index, and tensile elongation at the break decreases[21].

Once WPC has reached its end of life (EoL), separating the wood fibers and plastic polymers is problematic. As mentioned in the production section above, during agglomeration thermoplastic polymers are heated to the crystalline melting point and mixed with the wood fibers. This results in a mechanically irreversible bond between the wood and the plastic matrix [24]. Currently, according to Sommerhuber et al. [25] the recycling of WPC to a secondary material in order to improve resource efficiency is not economically viable.

The results of their assessment [25] of EoL options for WPC found that in an ideal situation, WPC would be recycled or reused in some manner, and doing so would be ecologically preferable. However, due to legislation regarding recycling, and a lack of market for recycled WPC material, incineration is the dominating method of disposal for WPC products.

1.4.2 WPC Market Potential

The market for WPC production in Europe more than doubled from 2000-2010. Table 3 shows the production growth from an estimated 3,000-15,000 tonnes in the year 2000 to an estimated 270,000 tonnes in 2010. As of 2017, the WPC market was valued at over 4.07 billion USD. Experts site WPC's perception as a low cost, environmentally friendly alternative to wood and plastic as the reason for market expansion [26]. The global market had a compound annual growth rate (CAGR) of 9.3% during the forecasting period 2018 – 2025 [26]. The CAGR is a measure of mean growth rate of an investment over a specified period longer than one year. It tells the investor what their investments yield on an annual basis. Which makes it a good indication of market health and method for evaluating how different investments have performed overtime [27][28].

Table 3. Estimates of WPC market development (tonnes) in Europe from 2000-2010 [23].

Year	Tonnes
2000	3000-50000
2002	15,000
2003	20,000-30,000
2004	-
2005	40,000-100,000
2006	50,000
2007	-
2010	270,000

The WPC market can be broken up by the type of plastic used in the composite blend. Predominantly, the market is divided into WPC made from, PE PP and PVC. In terms of revenue, PE has the greatest global market share at 65.9% in 2017 [26].

Table 4 shows the actual WPC production values for 2012 divided by sector, alongside the forecasted production in 2020 with and without market incentives. Construction and decking demands made up the majority of the European WPC market in 2012 followed by automotive needs. The forecasted demands for WPC are shown side by side with and without market incentive. An example of an incentive would be political stimulus of bio-economic products in the form of tax credits or subsidies. The difference between the 2020 market forecast, with and without incentivization, is roughly 50,000t for the construction and decking industry, 220,000t for the automotive industry, and 100,000t for the traded granulates industry.

Table 4. Forecasted WPC Production in 2020, with and without market political incentivization for the European market [23].

Bio Composites	Production in 2012	Forecasted Production in 2020 (Without incentives for bio-based products)	Forecasted Production in 2020 (with strong incentives for bio-based products)
WPC			
Construction and Decking	190,000 t	400,000 t	450,000 t
Automotive, Compression Molding& Extrusion/thermoforming	60,000 t	80,000 t	300,000 t
Traded Granulates for Extrusion and Injection Molding	40,000 t	200,000 t	300,000 t

1.5 Pallets

Pallets, quite literally, move the world. In the EU 20% of all sawn wood consumption is used to manufacture wooden pallets. According to the United Nations Economic and Social Council [29], this results in around 400 million new pallets produced annually in a pallet industry consisting of 3000 companies and employing over 50,000 workers. The majority of pallets produced, around 90%, are made from various types of wood and the remaining 10% are made from plastic, metal, corrugated cardboard, and composite material [30]. Each material has a tradeoff. For instance, stiffer materials will rack with other pallets more easily, but they are costlier. According to Pallet Enterprise [30], the three things that need to be considered when selecting a pallet are:

- pallet material and design
- load type and weight
- rack type and support span

Different industries have specific requirements for pallets. The health industry typically selects plastic pallets when shipping medicine or other medical supplies due to hygienic regulations. This is because plastic pallets are more resistant to bacteria than wood. As shown in Figure 7, there are two main types of pallets, stringer and block. Stringer pallets have wooden stringers that cover three sides of the pallet. They support the main load and run the entire length of the pallet from top to bottom. Typically, stringers are two-way pallets, meaning, the fork lift can access the pallet from only 2 sides. However, as shown in Figure 7, it can be modified for four-way entry. The pallet style refers to its basic construction. It can be double-faced non reversable, double-faced reversable, or single faced, The differing characteristic between the two is that single-faced pallets have one deck, colloquially referred to as skids, and double faced pallets have two decks, both a top and a bottom [31].

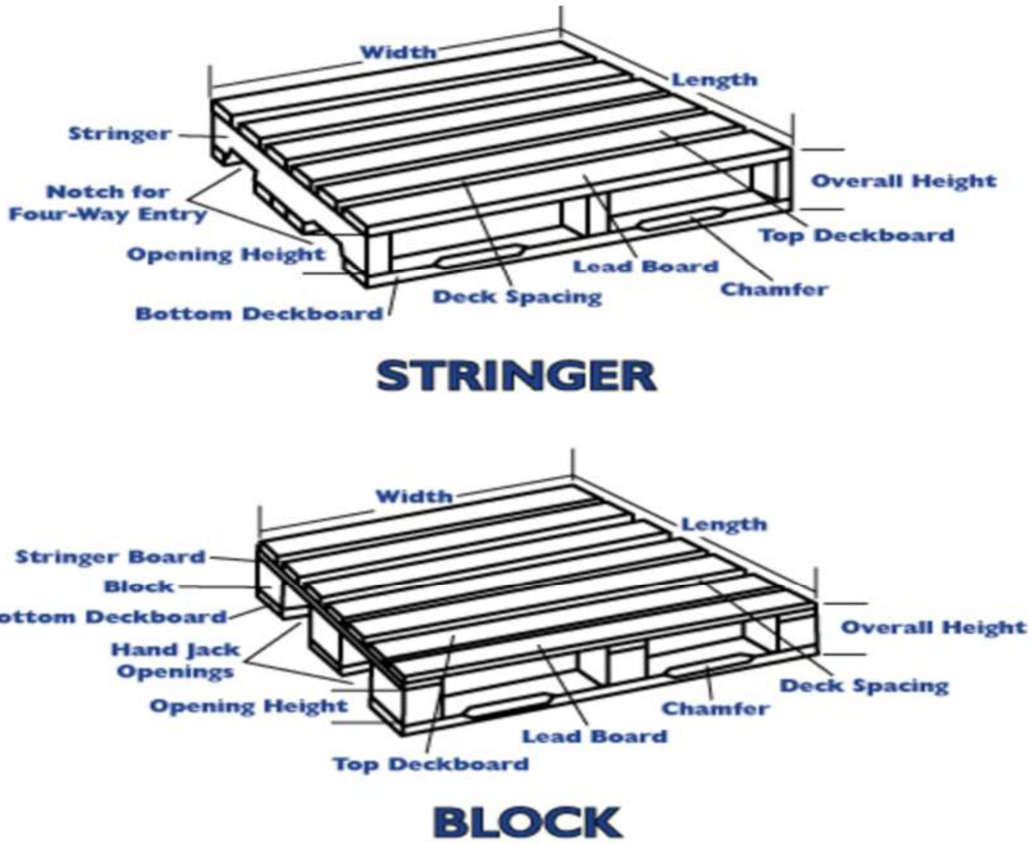

Figure 7. A diagram detailing the structure of the two main pallet typologies, stringer and block [32].

1.5.1 Pallet Management

There are three common business models that dominate the pallets industry: 1) single use expendable pallets 2) buy/sell programs 3) leased pallet pooling. In single-use expendable pallet systems, the ownership of the pallet is passed on with the load they carry. It does not return to the distributor or manufacturer and is made from inexpensive and expendable wood. In buy/sell programs, the company purchases the pallets from a manufacturer and internally manages them. When a pallet has reached the end of its useful life, the owner will bring them to a facility to recycle them or sell them to a pallet repair company who will fix the pallets and recirculate them. In the third system, pallet pooling, the customer rents the pallets from a distribution company who assumes the responsibility of managing the customers pallet pool. In order to do this, the leasing company will insert a contracted number of pallets upstream in the customers supply chain and then collect them downstream at designated collection facilities. They then repair them or, if they are unrepairable, place new pallets at the top of the echelon of the customer's supply chain [33]. Due to increases in material costs and expanding markets, the number of companies utilizing third party pallet management has increased [34]. From a cost perspective, it was found that the single use expendable pallet approach was the least costly of the three strategies, followed by the pallet pooling option [33].

1.5.2 Wooden Pallets

While there are currently no internationally standard pallet dimensions, The International Standards Organization (ISO) sanctions six standard wooden pallet dimensions as shown in Table 5. The most common pallet size used in Europe is the EUR pallet, with dimensions 1000x1200x144mm, which is also an ISO standard sized pallet. The wooden EUR pallet is made with 78 nails and is typically designed to be accessible from all four sides. Depending on the load requirements of the pallet the weight of a EUR Pallet can range from 20-35kg [35].

Table 5. ISO sanctioned pallet dimensions and European pallet dimensions along with the regions they are commonly used [35]

ISO Pallet Dimensions (mm)	Regions Commonly Used	Euro Pallet Type	Euro Pallet Dimensions (mm)
1016 × 1219	North America	EUR, EUR1	800 × 1,200
1000 × 1200	Europe and Asia	EUR 2	1,200 × 1,000
1165 × 1165	Australia	EUR 3	1,000 × 1,200
1067 × 1067	North America, Europe, Asia	EUR 6	800 x 600
1100 x 1100	Asia	Quarter Size	600x400
800 x 1200	Europe	Eighth Size	400 × 300

The wooden pallet manufacturing begins with felling of trees for lumber production. Round logs are harvested and sent to the sawmill for processing. The whole logs are then debarked and planed into green timber, or timber that has not been heat treated. The moisture content of the wood is a critical determinant of the pallet's load bearing performance. If a given moisture content is not specified, 19% is the rule of thumb [36]. The rough sawn timber is then usually purchased by a pallet manufacturer. Figure 8 shows a layout of small pallet company and the movement of the lumber though the production process. Raw pallet lumber enters a planner or ripsaw, then moves to the cut off area. The leading edge of the deck board may need to be chamfered. Additionally, if the pallet is a stringer pallet, the stringers need to be notched. The pallet is then drilled and assembled and leaves the processing plant as a completed pallet [36].The most common equipment used to manufacture wooden pallets is a three headed electric nailing machine [37].

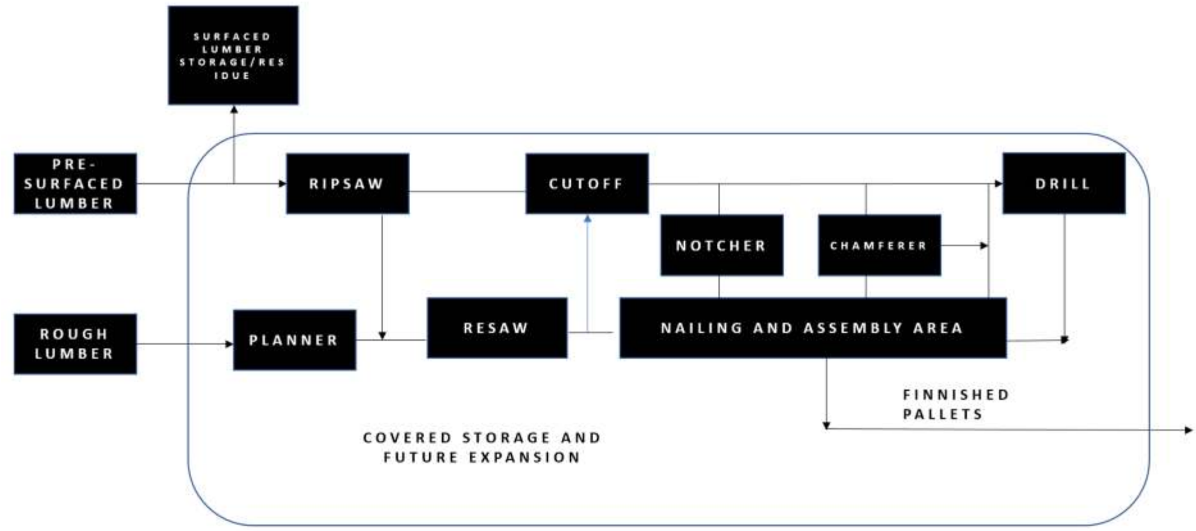

Figure 8. A detailed layout of a small wooden pallet manufacturing company with a maximum capacity of 500 pallets/day [36].

Due to wood's vulnerability to pest infestation, the European Union has sanitary standards for wooden pallets entering their borders. According to the current legislation wood packaging entering the EU must [38];

1. Be heat treated or fumigated with methyl bromide.
2. Be stamped with the International Phytosanitary Measures (IPSM) No. 15 mark[2]
3. Be debarked

The IPSM standard [39] defines a "repaired pallet" as a pallet that has had up to 30% of its original components removed or replaced. The new wood must abide by the IPSM standards and be marked with a new "wheat stamp". Any pallet that has more than 30% of its original material replaced is classified as "remanufactured". The old IPSM mark has to be removed, via paint or another measure, and the entire pallet has to be heat or chemically treated again [39].

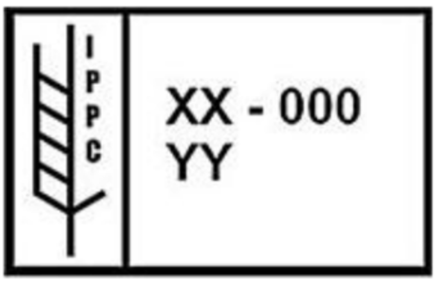

Figure 9. Commonly referred to as the wheat stamp, if a pallet bears the above figure it means it has been heat treated, or chemically treated in accordance with ISPM 15 measures [39].

A number of factors impact the performance and strength of wooden pallets. In loaded pallets, the wood carries the weight of the cargo like a beam, therefore bending strength is one of the most important characteristics of wooden pallets. Compressive strength, shock resistance, defects in the wood, and decay resistance are also telling factors of a pallets

[2] The IPSM standardization was instituted by the International Plant Protection Convention (IPPC) and applies to wooden packaging thicker than 6mm when crossing international borders. It requires pallets be heat treated or fumigated with methyl bromide. The ISPM mark is commonly known as the "wheat stamp" as its mark is a stalk of wheat (see Figure 9) [39].

performance [36].

1.6 Life Cycle Analysis

Life cycle thinking began in the early nineties when companies were called on to [40] "*develop criteria and methodologies for the assessment of environmental impacts and resource requirements throughout the full life cycle of products*." By the early aughts, the UNEP/SETAC life cycle initiative was born. Its main mission [40] was to "*develop and disseminate practical tools for evaluating the opportunities, risks and tradeoffs associated with products and services over their entire life cycle to achieve sustainable development*." Taking a full life perspective when evaluating a product or system avoids the shifting of problems from one life cycle or geographical area to another.

LCA is a holistic method that aims to quantify all the input and output related impacts emitted to or taken from the surrounding ecosphere during the life cycle of a product or system. LCA remains the only internationally standardized method of environmental product assessment. It is governed by ISO 14040 and 14044 standards [39] [40] which describes the principles and framework, and requirements and guidelines respectively. An LCA consists of four parts:

1.Goal and scope definition,
2.Life cycle inventory (LCI,)
3.Life cycle impact assessment (LCIA),
4. life cycle interpretation (Figure 10)

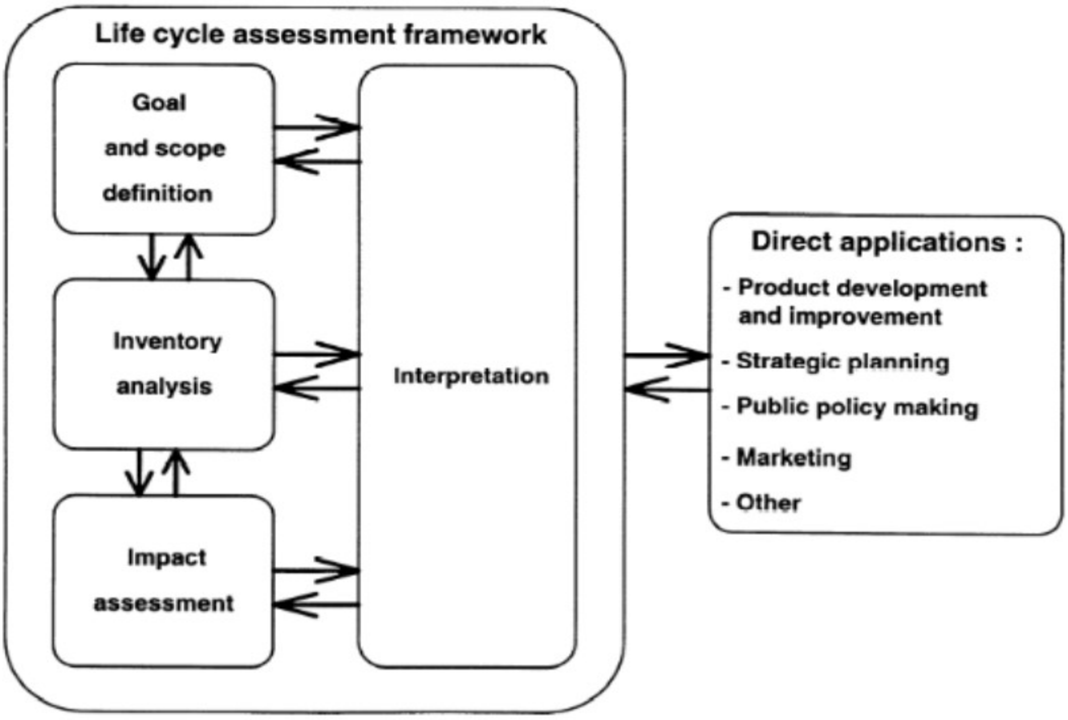

Figure 10. The stages of an LCA and its iterative nature represented pictorially [42].

The goal and scope definition acts as introduction to the LCA and denotes the purpose, systems under study, functional unit, and reference flow. The choice of impact categories and LCIA model needs to be explicitly stated as well. It should include all assumptions made in the duration of the LCA and allocation procedures. LCA is by no means a linear process. The goal and scope definition may need to be adjusted depending on data available or a system expansion due unforeseen co-products. The iterative process needs to be documented and any changes to the goal and scope definition need to be transparent. As shown in Figure 10, the arrows between the stages of the LCA indicate the bilateral relation between them and the revisioning processes.

In an ideal LCA, all inputs should be traced back to the system boundary between the Technosphere and the Ecosphere, and all outputs should be identified to the point where the emissions leave the Technosphere [43].

The LCI can be assembled once the goal and scope are clearly defined. First, a map of all unit processes should be created, listing all input and output flows to/from each process. The end result of the LCI is a tabular listing of all of the input resources taken from the environment and all of the outputted emissions released from the Technosphere to the Ecosphere. Data can come from primary or secondary sources but it is important that the quality, completeness, and consistency be in line with the goal and scope definition.

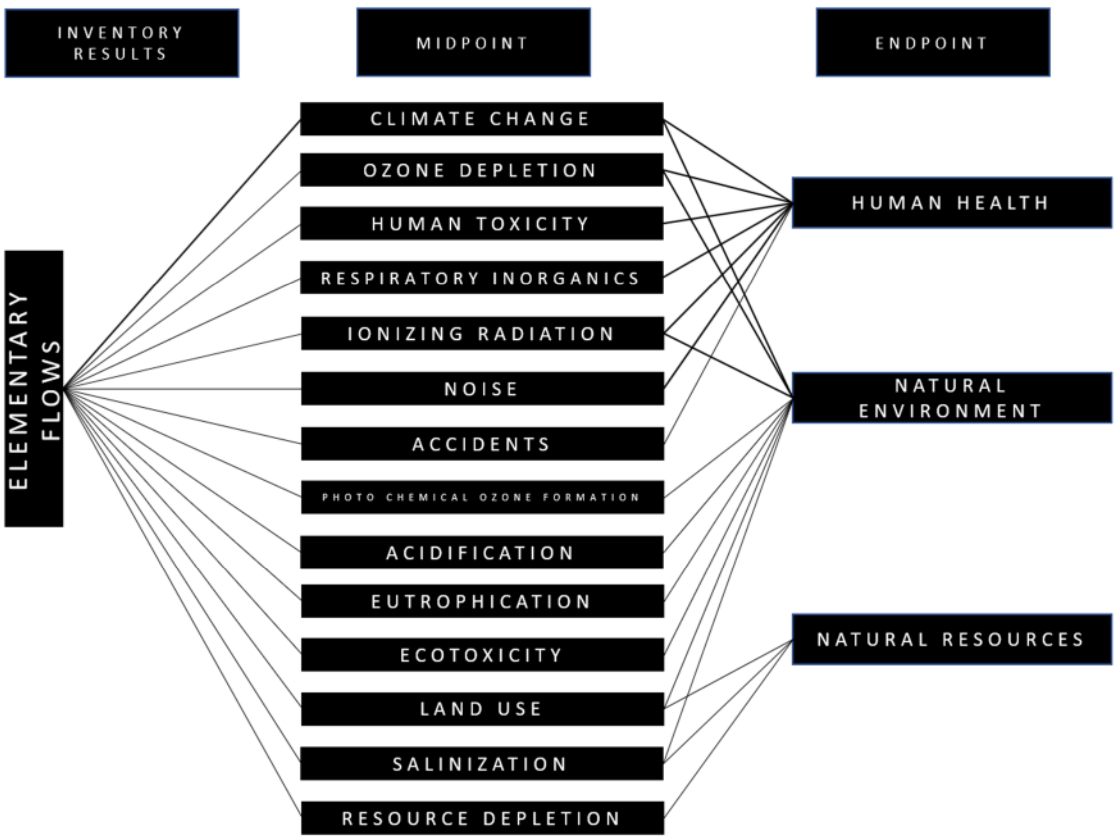

Figure 11. List of Midpoint and Endpoint Impact Categories [44]

The LCIA consists of mandatory steps and optional steps. The three mandatory steps in the LCIA are selection of impact categories, characterization and classification. A list of impact categories at both midpoint and end point can be seen in Figure 11. Midpoint impact categories are measured to the point where changes in the environment occur. Endpoint indicators go a step further and account for the actual damage done to human health, the natural environment, or natural resources. Characterization refers to the process of calculating all of the impact category results to a common unit, and the aggregation of those results within a common unit. Classification refers to the assignment of LCI results to an impact category.

Table 6 explains LCA terminology though the example of the acidification potential impact category [45]. The total amount of SO_2, NO_x, and HNO_3 etc. emitted from each unit process is the LCI result. The LCI results are assigned to the impact category, acidification potential (classification). The results are converted to kg SO_2 equivalent (characterization). This is done by multiplying the mass of HNO_3 by an equivalence factor, which is .51 for HNO_3 [45]. Once the LCI data is classified and characterized, the kg SO_2, eq. is the category indicator result.

Table 6- LCA Terminology Explained Through Acidification Potential [45].

Impact Category	Acidification potential
LCI Result	kg SO_2, kg NO_x kg HNO_3
Characterization Model	Accumulative exceedance
Category Indicator	An increase in acidity in moles H^+
Characterization Factor	Potential of each compound to cause acid depletion in relation to SO_2
Category indicator result	kg SO_2 equivalent
Category End Points	Increased acidity of soils and water, building corrosion

There are three optional steps in the LCIA; normalization, grouping, and weighting. Normalization gives context to the category indicator result by calculating the magnitude of the result relative to some reference information like regional emissions or emissions per capita. By looking at the relative magnitude of each impact category result, cross comparisons between systems or other impact categories have more context. Grouping is a ranking or sorting process for impact categories. Weighting refers to converting or aggregating indicator results across impact categories using numerically based factors or value choices [45].

In the final analysis stage, three checks need to be performed, a completeness, sensitivity, and consistency check. The goal of the completeness check is to ensure that all relevant data needed to perform the LCA is available and complete. A sensitivity check is used to examine the level of impact of uncertain data, allocation, or calculation of category indicator had on the results [45]. The consistency check is done to make sure that the goal and scope definition is in line with the other sections of the LCA.

1.7 Cost-Benefit Analysis

Assessing the overall sustainability of a product, system, policy, company etc. cannot be done with an environmental impact assessment alone. The concept of the triple bottom line was introduced by John Elkington [40] in the context of Corporate Social Responsibility. He stated that "*Triple bottom line accounting 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 make evaluation more in depth* This quote is now attributed to the idea of people, profit, and plant (see Figure 12) or the three pillars of sustainability; social, environmental, and economic. Including an economic valuation of the two pallet systems is in line with the three-pillar approach to sustainability assessments [32].

Figure 12. An Illustration of the tripple bottom line, showing the intersection of people, planet and profit [24]

Cost-benefit analysis (CBA) [46] is the elected method to address the economic costs of the pallets. CBA is a tried and true method used since the beginning of the 20th century in order to assess the attractiveness of new projects. The most common functional unit of a CBA is net present value (NPV) [27] (see equation 1.1) . A positive NVP would indicate that the project would return a profit.

$$NPV = \sum_{t=1}^{T} \frac{CF_t}{(1+x)^{t-1}} \tag{1.1}$$

where,

NPV= net present value
CF= cash flow
T= a designated period of time
X= the discount rate

Recent environmental and social concerns has led to the development of three types of CBA; fCBA, eCBA, and sCBA. fCBA, or financial CBA, is a tool for profitability assessments or feasibility studies. Only one stakeholder perspective is taken into account and as a result, one discounted cash flow is analyzed. If a capitalist market worked perfectly there would be no need for the other two CBA typologies, as the social cost and environmental cost would be reflected in the market price. However, the market, in the pejorative sense, is not perfect and externalities are the end result [28].

eCBA stands for environmental CBA. It was developed in the late sixties and early seventies out of environmental concern. It attempts to assign monetary value to the damage caused by negative environmental externalities. As the polluter is usually not the one who pays, assigning monetary value to climate impacts is very difficult. The NPV in an eCBA will only be positive if the financial benefits do not exceed the environmental cost.[28]

sCBA evaluates a project from the perspective of society. The unit in sCBA is also money, but the objective is to evaluate the welfare. Using money as a common unit allows for cross project comparison. Some examples of quantified costs are health care costs, maintenance costs, EIA costs, and costs that arise from unsafe working environments.

Similarly, to end point indicators in an LCA, quantifying impacts on human health and the environment is a tricky business. The manifestations of negative or positive impacts could take decades and it is impossible to isolate the subjects from being exposed to a plethora of other impacts. In order to more accurately represent the social cost of a project, weighting can be used. In the case of sCBA a project is only viable if the financial costs do not exceed the social cost after weighting.

1.8 Research Aim and Questions

The goal of this thesis is to investigate the environmental and economic impacts of pallets made from CDW based WPC and compare them to pallets manufactured from virgin wood. The aim in comparing the two products is to better understand the consequences of using repurposed waste to replace an item made from biomass with a dominant global market share. In order to accomplish this, an LCA will be conducted to measure the GWP of both pallet systems, and a CBA will be completed to assess the economic consequences of relevant stakeholder decisions. The following research questions will be addressed:

1. Which pallet system has a lower impact on the GWP for 1000 pallet trips?
    a. Which life cycle stage of each pallet system has the highest GWP?
    b. How do changes in the transport utilization factor impact the use phase?
    c. How do different repair/ handling scenarios impact the results?
    d. Does the recycling of unrecovered CDW have a net positive impact on the GWP?
2. From the perspective of the pallet pooler, how does the cost of managing WPC or wooden pallet compare for 1000 trips?
    a. Which raw material has the highest percentage cost per unit?

Chapter 2

Literature Review

The following section will serve as a literature review of the state of the field with regard to LCA studies of wood plastic composite products.

2.1 Literature on WPC and CDW

As observed by Liikanen et al. [22] in their paper on the environmental impacts of using CDW as a raw material for WPC, LCA studies of wood composite products can largely be divided into two groups, those that compare WPC to other materials and those that assess the environmental impact of various raw material sources.

K. Manninen et al. [16] conducted research on utilizing wood waste for WPC production. The composition ratio of WPC in the study was 60% recycled wood fiber, 30% plastic, half of which was recycled, and the remaining 10% was UV protectants and other fillers. The LCA was based on the avoided impacts of replacing a terrace board made from virgin wood with a board of the same dimensions made of WPC. The results show that the most significant climate change impacts were caused by producing the virgin plastic and the production both of which consumed a lot of energy. Virgin plastic was also the most impactful with regards to acidification potential. The authors noted that only 20% of the impacts from plastic were due to the recycled half of the PP. They found similar results for the eutrophication impact category as well. Overall, they concluded that more emissions were generated than avoided across all impact categories. However, the variation in their uncertainty analysis made the results less clear.

O. Väntsi and T. Kärki [47] looked at the *environmental assessment of recycled mineral wool and polypropylene utilized in wood polymer composites.* Their LCA had two main goals (1) to environmentally compare the performance of recycled mineral wool to glass fiber as a filler in WPC and (2) to compare the environmental performance of waste recovered plastic polymers to virgin polymers. The functional unit of the study was 100kg of extruded decking boards and as such the use phase was excluded. Four different scenarios were presented, each with a different WPC composition blend. Along with two end of life scenarios, landfilling and incineration. They found that the scenario which was a composite blend of 70% wood and 30% recycled PP had the lowest impact on the global warming potential, in both the landfill and incineration scenario. Incineration was favorable option for the end of life scenario in all four composite blends, with the mineral wool blend preforming best. In sum, the study showed that recycled PP can be an environmentally suitable material for the production of composite products and that incineration was a more environmentally friendly way of disposing of the material when compared with the landfilling scenario.

As a part of her PhD dissertation Anna Keskisaari [48] co-published an article looking at using CDW based mineral fillers in WPC. Two different CDW blends were assessed; one containing waste mineral wool and plasterboard, and the other, a mixed blend of CDW. They found that the added mineral wool decreased the flexural strength and modulus values of the polypropylene blended with it. But also, that the added mineral wool increased the impact strength.

P. F. Sommerhuber [25] and associates completed an LCA on WPC. They analyzed alternative materials and identified an environmentally sound end of life option. The aim of the study was to evaluate the environmentally preferable material, WPC made from virgin material or made from secondary source, and to discover which EoL option, utilization as a secondary fuel, or as a secondary material, has a lower environmental impact. The two distinct research questions essentially split the assessment into two sperate LCAs, a product LCA, and a systems LCA. In order to compare the two products and systems a "basket of benefits" approach was used. This is a unique LCA approach that looks at the energy use per functional unit which allows for comparison despite different end uses of the system [49][45]. For the product LCA addressing RQ1 the function unit, was 1kg of WPC material. The method of production was not specified i.e. extrusion or injection molding. The results showed that the environmental impacts are lower for WPC produced from secondary sources when compared virgin materials in all impact categories studied except for acidification potential (ADPE) and photochemical oxidation poential (POCP), which is due to the emissions to air during the wood particle drying process. For the second research question, they found that the recycling of post-consumer waste is more preferable than incineration, and that WPC has more in common with solid plastics at its end of life phase and needs to be treated as such.

M. Liikanen et al. [22] researched alternative uses for CDW. They compared the utilization of CDW for WPC production to a baseline scenario where C&D waste fractions are either incinerated or put to landfill. They found that the GWP and fossil fuel demand was lower when CDW was used as a raw material for WPC production, when compared to incineration and landfilling. If WPC is used as a substitution for virgin plastic and aluminum the impact on the GWP was found to be favorable. Though the authors noted that due to differences in mechanical properties WPC cannot directly substitute either material on a 1:1 basis. The minimum substitution threshold to achieve environmental benefits was found to be 6% for plastic and 8% for aluminum.

A. Keskisaari and T. Kärki [50], examined the profitability of using waste materials in wood-plastic composites. They used six different waste-based composites scenarios and compared them to a baseline composite made from virgin material. They separated the costs between material costs and manufacturing costs. They found that the price of recycled material does not play a major role in the total price of the WPC. They also found that virgin plastic was the most expensive raw material in the WPC blend and accounted for over half of the raw material cost. For the manufacturing costs of WPC, they found that extrusion was by far the most expensive of the processing steps. Labor costs were not considered.

A. Di Maria et al. [51] evaluated four end of life options for CDW; downcycling, landfilling, advanced recycling, and recycling after selective demolition. When combining economic cost and environmental impact, landfilling was found to have the highest associative cost and highest environmental impact. Landfill taxes were the identified as the reason for the high cost.

I. Turku et al. [52] authored an article on the impact of using recycled plastic blends in WPC. They looked a light plastic waste fraction from CDW and mixed household waste. They found that when compared to virgin plastic (LD-PE), the strength of the WPC was poorer. They were both equally hard, and the WPC was found to be stiffer than the virgin plastic.

L. Jingkuang, and W. Yousong [53] did a cost analysis of CDW management in China. They compared the costs of landfilling, recycling, and reuse. They found that landfilling 1 ton of CDW in River Delta region from 2010-2013 costs about 87.81 yuan, recycling costs 76.83 yuan/ton and reusing the CDW costs 23.29 yuan/ton. There scope was site collection management to recycling treatment. They concluded that on an equal basis recycling-based reuse cost the least among the three recycling options.

2.1 Literature on Pallets

This section presents a comprehensive literature review on various aspects of the pallet industry, from LCA studies to costing analysis.

J. Almeida and J. Bengtsson [54], carried out an attributional LCA for a company that produces waste plastic pallets called Re>pal. They did a cradle to grave comparative study of recycled plastic, virgin wood, and virgin plastic pallets. The functional unit of the study was 1 pallet trip. They completely excluded pooled pallets and only modeled single use pallets. In the EoL scenario, landfilling and municipal incineration was included along with recycling and mulching for the timber pallet. The results showed that of the pallet life cycle stages, transport accounted for 57% of climate change impact, followed by manufacture (28%) and EoL (10%).

Carrano et al. [37] did a two year study on operations that take place during a wooden pallet life cycle. The aim of their research was to find the best method for estimating the carbon footprint of a wooden pallet. The results were partitioned by life cycle stage. For raw material extraction, they found that wood accounted for 82% of the total GHG emissions, while steel alloy was responsible for the remaining 18% in the form of steel fasteners and nails. For the pallet manufacturing process, they found that the majority of emissions comes from the heat treatment process and that GHG emissions from pallet assembly only accounts for a small fraction. In the use life cycle stage, the impact was a result of the tare weight of the pallet and the mode of transportation. The end of life phase GHG impacts varied greatly depending on method of disposal.

R. Farreny et al [55] completed a Life cycle assessment of a coniferous wood supple chain for pallet production in Catalonia, Spain. The pallets in their study were made of virgin sawn wood. They found that energy consumption was the most impactful input of wooden pallet production, followed by the pesticide used to treat the wood.

K. S. P. Anil [56] completed his master’s thesis on an Environmental Analysis of Pallets Using Life Cycle Analysis and Multi-Objective Dynamic Programming (MODP). The focus of his study was to compare the environmental performance of wooden and plastic pallets and explore the impacts of various pest treatment methods. He found that when comparing virgin wood pallets and virgin plastic pallets in a MODP setting, wood pallets were the more preferable option for the environment. When he adjusted his MODP model to decide between the two on solely a cost basis, the plastic pallet was found to be superior. He concluded that this was likely due to the fact that the life cycle of the wooden pallet, before repair, was around 20 trips and the plastic pallet was 70. In terms of wood pallets treatment method, he found that methyl bromide fumigation has the highest ODP impact but that in all other categories, heat treatment was more impactful.

Park et al.[57] built gate-to gate LCI data for the repair process of wooden pallets. They looked at the repair of 1219x1016 mm stringer-class pallets, and collected data from seven different repair facilities. He found that the repair equipment had the largest contribution of the GHG emissions. Also, that the steel nails for pallet repair had the largest impact on the GWP. For their GWP calculation they counted salvaged wood from other pallets as a negative emission. Because of this, they found that the GHG emissions of the repair process was negative.

A. Ustundag [58] did a cost benefit analysis of the utilization of RFID devices for pallet polling systems. The used scenario-based cost benefit to evaluate the potential impacts of RFID on pallet pooling. The supply chain modeled consisted of a pallet supply company and three customers. They used a model that calculated total NPV of labor cost savings, inventory cost reduction, profit shrinkage, lost pallet cost reduction, and pallet retail cost reduction for both the pallet supplier and the three customers. They found that the NPV was positive for both the supplier and the customer. While RFID is not considered as a part of this thesis, the methodology was critical in shaping the approach to the CBA done below.

Alvarez and Rubio [59] used a compound method, called MC3, that blends a financial input/output analysis and a process-based analysis in order to calculate the carbon footprint of a wooden pallet from cradle to gate. Their aim was to compare their hybrid method to the traditional process-based method. They found that their hybrid model reported 22% higher emissions than the ones from the process-based analysis.

J. Bengtsson and J. Logie [60], assessed the performance of pooled pallet alternatives compared to one-way pallets. They compared softwood pooled pallets, hardwood pooled pallets, plastic pallets, and compressed cardboard pallets to simple one-way softwood pallets. He found that of the five pallet types compared, softwood pooled pallets had the best environmental performance.

R. Elphick-Darling and V. Jayasooriya [61] completed a LCA on three different pallets; a CME composite pallet, a pooled timber pallet, and a pooled plastic pallet. The functional unit of their study was 1000 pallet trips and the associated reference flows can be seen in Table 7. The pallet dimensions were standard Australian sized (1165x1165x150mm) and the composite pallet was made from glass filled polypropylene. They found that in all 13 impact categories studied, the composite pallet was the most environmentally favorable in the transport, disposal and use life cycle stages. However, the energy footprint of the CME pallet was higher than the other two which lead to higher environmental burdens during the production phase

Table 7. Functional Unit, Pallet Life Time and Expected Life of a Plastic Pallet, Composite Pallet, and a Pooled Timber Pallet [61].

PALLET TYPE	FUNCTIONAL UNIT (TRIPS)	PALLET LIFE TIME (TRIPS/PALLET)	FUNCTIONAL UNIT (PALLET)
CME COMPOSITE MATERIALS PALLET	1,000	150	7
POOLED TIMBER PALLET	1,000	83	12
POOLED PLASTIC PALLET	1,000	63	16

C. Gasol et al. [62] did an LCA comparing the environmental impacts of different reuse intensities for industrial wooden containers. They examined a high reuse pallet, a low reuse pallet, low reuse spool, and null reuse spool. They concluded that a higher reuse intensity was correlated to a reduction in energy use and virgin wood consumption. For the pallets they found that transport, raw material extraction, and the process chain life cycle stages had the highest environmental footprint.

Chapter 3

Methods

3.1 Life Cycle Analysis

An LCA was carried out in accordance with ISO 14040 and ISO 14044 [25] [26]. The goal and scope definition, life cycle inventory, life cycle impact assessment, and life cycle assessment are listed below. The goal and scope definition and LCI are presented in the methods chapter and the LCIA and analysis are listed in the results and discussion chapter.

3.1.1 Goal and Scope Definition

3.1.1.1 Goal

The intended application of this LCA is to assess the environmental impacts of using CDW as an alternative raw material for pallets in lieu of virgin wood. The purpose of this study is primarily an educational exercise in utilizing LCA methodology to complete a sustainability analysis and the results should be taken as such.

3.1.1.2 Scope

The two product systems to be studied are the life cycles, from cradle to grave, of CDW based WPC pallets and pallets made from virgin wood. The functions of these two products are to facilitate trade by carrying goods between destinations. Pallets expedite the shipment of products by providing forklifts uniform grip space to unload cargo to or from shipping vehicles.

Functional Unit:

Table 8. Description of the functional unit, reference flow, design, and dimensions of the WPC and wood pallets.

Pallet	Dimensions	Weight	Design	Functional Unit	Reference Flow	Repair Frequency
WPC Pallet	200x800x140mm	22 kg	Stringer Pallet Double-faced reversable	1000 Pallet Trips	7 Pallets	47 trips
Wooden Pallet	200x800x140mm	34 kg	Stringer Pallet Double-faced reversable	1000 Pallet Trips	12 Pallets	27 trips

The functional unit for this thesis is 1000 pallet trips. The respective reference flows, or the number of pallets required to complete 1000 trips, will be 12 virgin wood pallets and 7 WPC pallets. 1000 trips is consistent with literature on LCAs of pallet supply chains and the number of pallets used in the reference flow is taken from [61]. The job of the reference flow is to translate the abstract functional unit into a specific product flows for each of the analyzed product systems. During the loaded stage of the use phase, when the pallet is carrying cargo, it is assumed that both the pallets will be carrying 500kg worth of material. The dimensions of the wood pallet are the EURO pallet standard, 1200x800x140mm. The wooden pallet is a four-way pallet, held together with 78 steel nails and weighs 34kg.The WPC pallet modeled will be assumed to have the same dimensions though with a lighter weight, 22kg. The above information is summarized for in

Table 8. The composite blend values used though out the LCA can be seen in Figure 13. The recipe used in this model was adapted from [22], [25], [47].

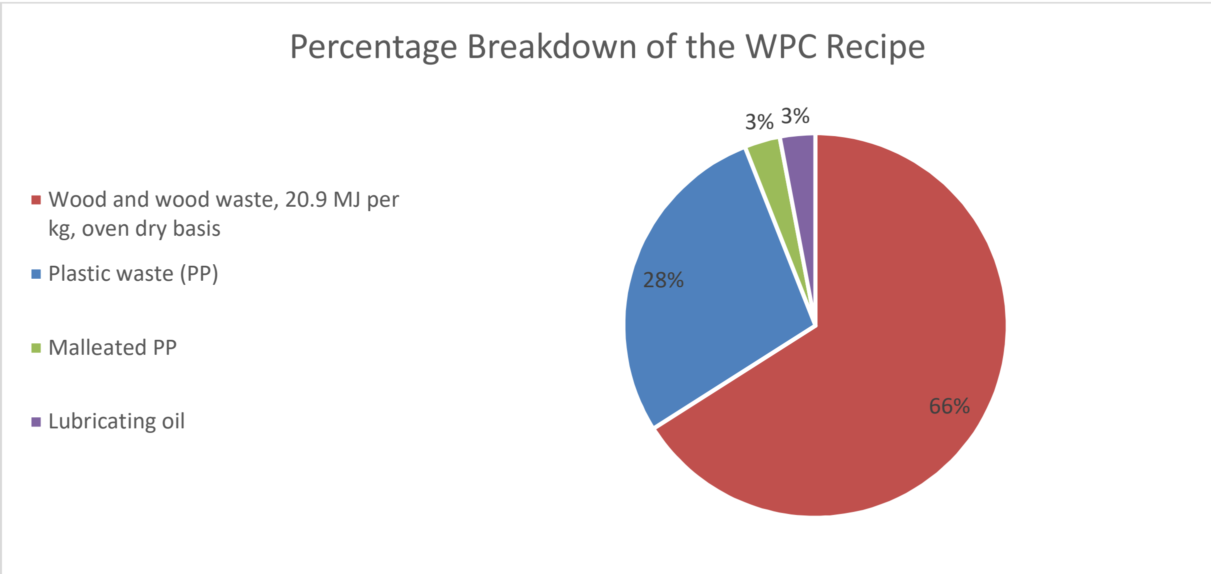

Figure 13. Percentage breakdown of the WPC pallet per component ingredient of the pallet [22], [25], [47]

Data Sources and Quality: The data gathered for this LCA was obtained through an extensive literature review. As such, all of the data presented in this thesis is from a secondary source. Due to confidentiality issues, primary foreground data could not be obtained. The use phase of the pallet life cycle was modeled after an interview with an operations manager at Chemp Pallets [63]. His insight into the movements of pooled pallets during their use phase stands as an expert estimation. As there is a lack of primary data taken from the pilot plant or a wooden pallet manufacturer, it should be stated again that the results of this LCA are not intended to be objectively authoritative. Nor do they intend to give absolute emission values. The two pallet systems were modeled with Gabi Educational Database 2018.

System Boundary: The life cycle stages addressed in this LCA and corresponding system boundary can be seen in Figure 14 and Figure 15. Not included in the system boundary are;

- The manufacturing of capital equipment
- Internal transportation
- Treatment of unrecovered CDW not used for the WPC production
- The upstream production and transportation of MAPP

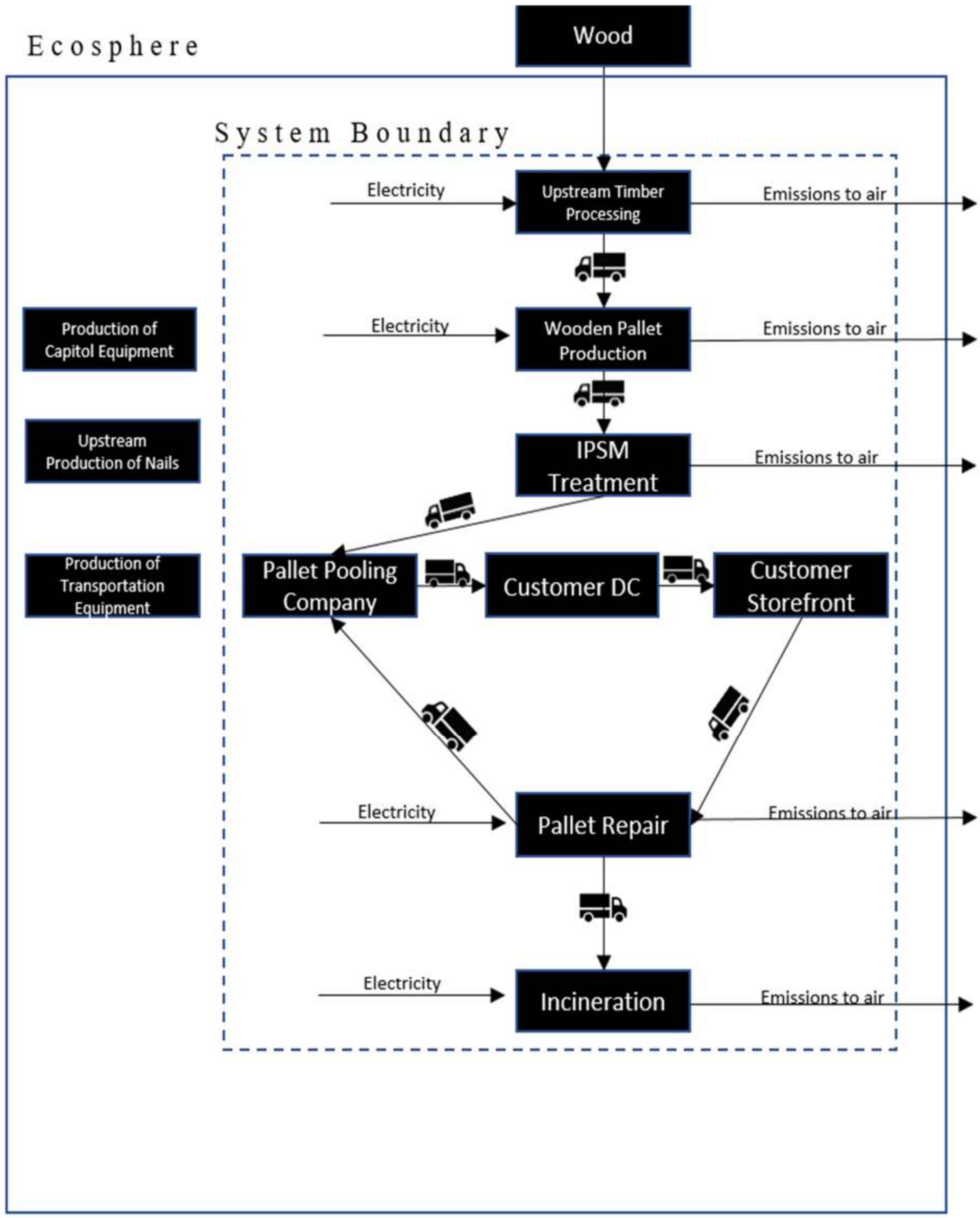

Figure 14 System boundary diagram for wooden pallet life cycle.

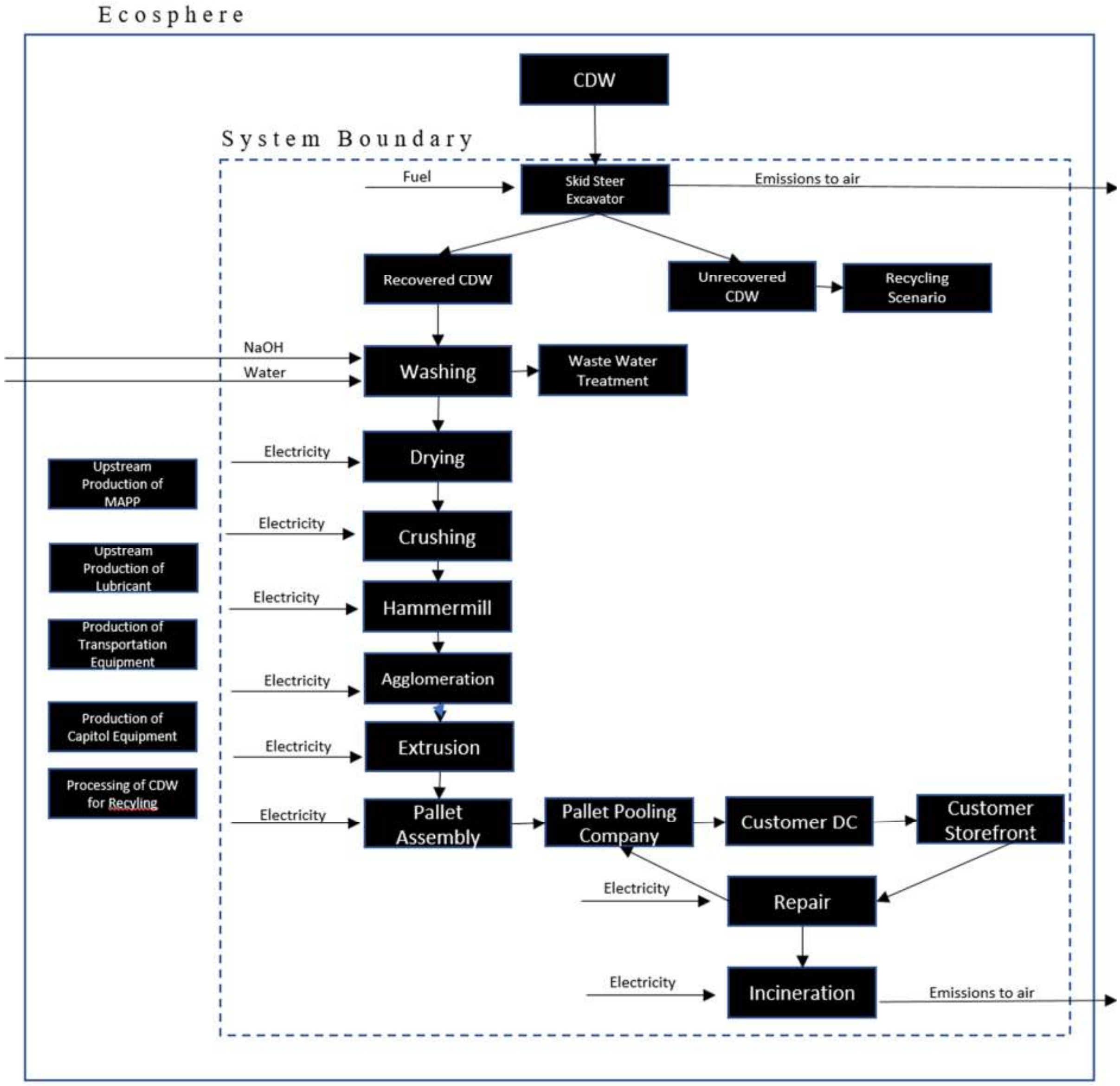

Figure 15. WPC pallet life cycle unit processes and system boundary.

The unrecovered CDW, shown above in Figure 15, is a co-product of the recovery of CDW. To account for this, the system was expanded to model a recycling scenario where the unrecovered CDW replaces virgin material.

Allocation Procedures: Allocation was not utilized in this study, the systems were expanded to include the energy recovered from incineration, the recycling of unrecovered CDW, and the treatment of waste water.

LCIA Interpretation and Impact Category Selection: The LCIA interpretation methodology utilized for this LCA is CML 2001- Jan. 2016 as it is a widely recognized and respected model. GWP is the impact category chosen for this LCA. The characterization models and category indicators chosen for the GWP impact category can be seen in Table 9. Hauschild et al. [64] classified this model for GWP as I. Which means that it is recommended and satisfactory. They reported that the GWP as published by the Intergovernmental Panel on Climate Change (IPCC) is the most current and well-researched, consensus-based model, available. No endpoint impact categories were chosen for this study. It is the authors opinion that to include endpoint indicators on an LCA conducted with solely secondary data would be a further abstraction of already abstracted data.

Table 9. Best available characterization models at midpoint [64].

Impact Category	Best Among Existing Characterization Models	Indicator	Classification
Climate Change	Baseline Model of 100 Years of the IPCC [65]	Radiative forcing as Global Warming Potential (GWP 100)	I.

Assumptions: It is assumed that the environmental impacts from the previous life of the WPC product are not accounted for in this LCA. This is called the zero-burden approach [66]. It is also assumed that there is no loss of wood or plastic during the production process. That the mass of wood and plastic entering each unit process leaves each unit process. The number of WPC pallets needed to fulfill the functional unit of 1000 was taken from [61]. It was assumed that though the composite pallets in their study were produced via compression molding, and made with glass fibers, that it would also require 7 WPC pallets made from CDW to complete 1000 trips. The data for the production of wood pallets was taken from [60]. The Chinese pallet, used in their study had relatively the same dimensions of a EURO pallet, therefore it was assumed that the production inputs/outputs would be the same

In order to account for the repair phase of the pallet life cycle, three scenarios (High intensity, medium intensity, and low intensity) were modeled to simulate the impact pallet handling has during the use phase. High intensity handling represents rough conditions, i.e pallets crushed, tossed, cracked, etc., and 40% of the repair material has to come from freshly extruded C&D waste or pallet timber. Medium intensity repair signifies 30% of the pallet needing to be repaired with new material, and 15% for the light intensity model. The nails are assumed to be common helical nails weighing 4g each.

3.1.2 LCI

The purpose of the LCI is to list all inputs from the Ecosphere to the Technosphere and all outputs from the Technosphere to the Ecosphere. The following section will break each pallet life cycle into its respective phases and discuss the various inputs and outputs for the corresponding unit processes. The data reported for each unit process reflects a high intensity repair scenario.

3.1.2.1 WPC Pallet

Raw Material Sourcing: a skid steer excavator is used to recover the CDW wood and plastic. The data on the recovery capacity and diesel consumption is taken from [47] and the data on the fuel emissions to air is taken from [67]. The raw material sourcing life cycle stage includes the recovery of CDW for eventual pallet production and the recovery of the unusable or unrecovered CDW. Table 10 shows the LCI data for the skid steer excavation unit process. The GWP emissions are a result of the fuel consumed by the excavator.

Table 10. LCI data for the skid steer excavation unit process.

Skid Steer Excavation	Unit	Amount	Source
Inputs			
Diesel consumption in construction machine	kg	16.1	[47], Calculated
Product waste (plastics)	kg	58.8	[22], Estimated
Wood and wood waste	kg	137.2	[22], Estimated
Construction waste (unspecified)	kg	28	[47], Calculated
Outputs			
Wood and wood waste	kg	137.2	[22], Estimated
Product waste (plastics)	kg	58.8	[22], Estimated
Carbon dioxide [Inorganic emissions to air]	kg	49.8	[47], Calculated
Construction waste (unspecified) [Stockpile goods]	kg	28	[47], Calculated
Methane [Organic emissions to air (group VOC)]	kg	0.03	[47], Calculated
Nitrous oxide (laughing gas) [Inorganic emissions to air]	kg	0.002	[47], Calculated

The waste fraction shown in Figure 16 [68] was applied to the unrecovered waste. The resulting masses of the unrecovered waste can be seen in Table 11. It was assumed that all waste wood was recovered and that all *other* material listed in the pie chart was recovered as plastic for the WPC blend or glass for the recycling scenario. The total amount of unrecovered CDW was calculated as 20% of the total volume of CDW entering the system. The glass, metal and mineral wool are then modeled against the upstream production processes of their virgin material counterparts.

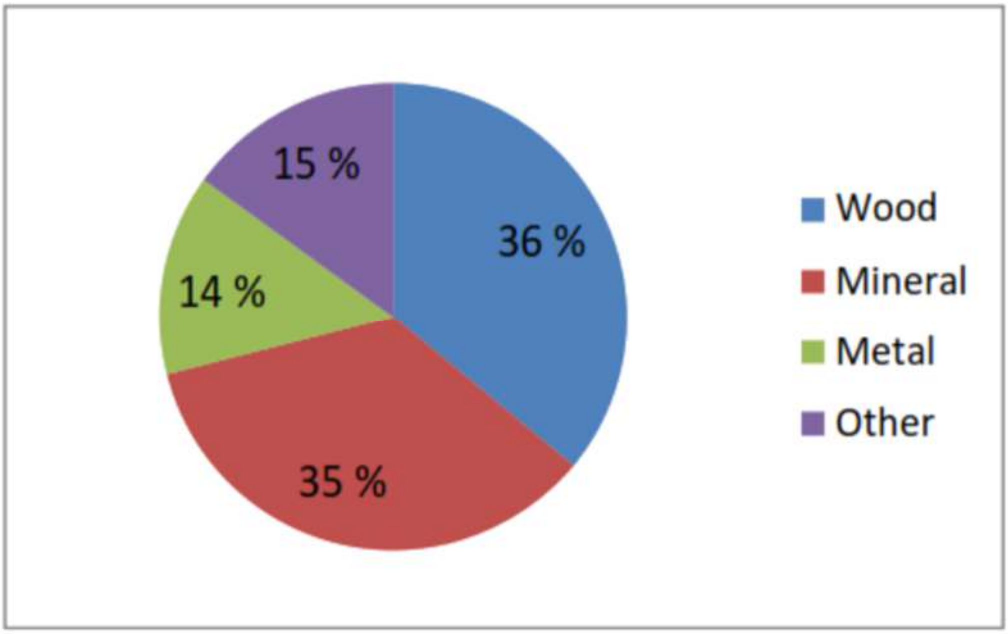

Figure 16. Approximate C&DW Waste Fraction Taken from Finnish Construction Sites [68].

Table 11. Unrecovered CDW calculated composition.

Total Un-Recovered CDW (kg)	**Glass fibers (kg)**	**Metal (kg)**	**Mineral Wool (kg)**
28	2.1	3.9	9.8

Table 12. LCI Data for the virgin material replaced by CDW in the recycling scenario

Recycling Scenario	**Unit**	**Amount**	**Source**
Inputs			
DE: BF Steel billet / slab / bloom ts <p-agg>	kg	3.9	[22], Estimated
DE: Glass fibres ts	kg	2.1	[22], Estimated
EU-28: Stone wool ts	MJ	9.8	[69], Calculated
Outputs			
Carbon dioxide [Inorganic emissions to air]	kg	12.8	[22], Estimated
Carbon dioxide (biotic) [Inorganic emissions to air]	kg	.1	[22], Estimated
Methane [Organic emissions to air (group VOC)]	Kg	.01	

Table 12 shows the LCI for the virgin material replaced by the unrecovered CDW waste in the recycling scenario. The GHG emissions from the production of each raw material are offset by the recycling of the unrecovered CDW.

Production: The production phase of the WPC life consists of the unit processes; washing, the treatment of waste water, drying, crushing, hammermill, agglomeration, extrusion, and pallet assembly. The data for each unit process can be seen in Table 13-20.

Table 13. LCI data for the washing process (WPC pallet).

Washing	**Unit**	**Amount**	**Source**
Inputs			
Wood and wood waste	kg	137.2	[22], Estimated
Water	kg	783.2	[47], Calculated
Sodium hydroxide (100%; caustic soda)	kg	0.2	[47], Calculated
Wood and wood waste	kg	58.8	[22], Estimated
Outputs			
Water (desalinated; deionized) [Operating materials]	kg	783.1	[47], Calculated
Wood and wood waste, 20.9 MJ per kg, oven dry basis [Renewable resources]	kg	137.2	[22], Estimated
Product waste (plastics) [Consumer waste]	kg	58.8	[22], Estimated
Sodium hydroxide (100%; caustic soda)	kg	0.2	[47], Calculated

Table 14. LCI data for wastewater treatment process (WPC pallet).

Waste Water Treatment	Unit	Amount	Source
Inputs			
Water (desalinated; deionized) [Operating materials]	kg	783.2	[47], Calculated
Steam (MJ) [steam]	MJ	80.0	[70]
Electricity [Electric power]	MJ	2.2	[70]
Hydrated lime dry slaked [Minerals]	kg	0.9	[70]
Iron chloride [Inorganic intermediate products]	kg	0.4	[70]
Outputs			
Nitrogen [Inorganic emissions to fresh water]	kg	0.1	[70]
Processed water to river [Other emissions to fresh water]	kg	783.2	[47], Calculated
Nitrate [Inorganic emissions to fresh water]	kg	0. 1	[70]

Table 15. LCI data for drying unit process (WPC pallet).

Drying	Unit	Amount	Source
Inputs			
Electricity [Electric power]	MJ	<0.0	[69]
Wood and wood waste, 20.9 MJ per kg, oven dry basis	kg	137.2	[69]
Product waste (plastics)	kg	58.8	[69]
Outputs			
Wood and wood waste, 20.9 MJ per kg, oven dry basis [Renewable resources]	kg	137.2	[69]
Product waste (plastics) [Consumer waste]	kg	58.8	[69]
VOC (unspecified) [Organic emissions to air (group VOC)]	Kg	.13	[69]

Table 16. LCI data for crushing unit process (WPC pallet).

Crushing	Unit	Amount	Source
Inputs			
Wood and wood waste, 20.9 MJ per kg, oven dry basis [Renewable resources]	kg	137.2	[22], Estimated
Product waste (plastics) [Consumer waste]	kg	58.8	[22], Estimated
Electricity [Electric power]	MJ	85.2	[69], Calculated
Outputs			
Wood and wood waste, 20.9 MJ per kg, oven dry basis [Renewable resources]	kg	137.2	[22], Estimated
Product waste (plastics) [Consumer waste]	kg	58.8	[22], Estimated

Table 17. LCI data for hammermilling process (WPC pallet).

Hammermill	Unit	Amount	Source
Inputs			
Wood and wood waste, 20.9 MJ per kg, oven dry basis [Renewable resources]	kg	137.2	[22], Estimated
Product waste (plastics) [Consumer waste]	kg	58.8	[22], Estimated
Electricity [Electric power]	MJ	490.0	[69], Calculated
Outputs			
Wood and wood waste, 20.9 MJ per kg, oven dry basis [Renewable resources]	kg	137.2	[22], Estimated
Product waste (plastics) [Consumer waste]	kg	58.8	[22], Estimated

Table 18. LCI data for the agglomeration unit process (WPC Pallet).

Agglomeration	Unit	Amount	Source
Inputs			
Wood and wood waste, 20.9 MJ per kg, oven dry basis [Renewable resources]	kg	137.2	[22], Estimated
Product waste (plastics) [Consumer waste]	kg	58.8	[22], Estimated
Malleated PP [Binder]	kg	5.9	[22], Estimated
Lubricating oil [Operating materials]	kg	5.9	[22], Estimated
Electricity [Electric power]	MJ	282.2	[22], Estimated
Outputs			
Wood and wood waste, 20.9 MJ per kg, oven dry basis [Renewable resources]	kg	137.2	[22], Estimated
Product waste (plastics) [Consumer waste]	kg	58.8	[22], Estimated
Malleated PP [Binder]	kg	5.88	[22], Estimated
Lubricating oil [Operating materials]		5.88	[22], Estimated

Table 19. LCI data the extrusion unit process (WPC Pallet)

Extrusion	Unit	Amount	Source
Inputs			
Wood and wood waste, 20.9 MJ per kg, oven dry basis [Renewable resources]	kg	137.2	[22], Estimated
Product waste (plastics) [Consumer waste]	kg	58.8	[22], Estimated
Malleated PP [Binder]	kg	5.9	Estimated
Lubricating oil [Operating materials]	kg	5.9	[70]
Electricity [Electric power]	MJ	252.0	[22], Estimated
Outputs			
Extrusion Mix	kg	207.76	[70]

Table 20. LCI results for pallet assembly (WPC Pallet).

Pallet Assembly	Unit	Amount	Source
Inputs			
Extrusion Mix	kg	207.8	[70]
Steel billet (St) [Metals]	kg	2.1	Estimated
Outputs			
WPC Pallet [Packaging]	kg	210.7	Calculated

Use: [63] During the use phase of the pallet, the pallet is shipped from the production facility to the pallet pooling company. The pallet poolers enter the pallet in the customers supply chain where the pallet is loaded and sent to the customer store front. The pallet is then recovered and inspected at the pallet pooling company's warehouse. There, the pallet is either repaired and reinserted in the customer's supply chain or sent to its EoL. On average each WPC pallet will run through this chain 142 times, and is repaired every 45-47 trips. The transportation distances and trucks used for transport are shown in in Table 21.

Table 21. Transportation distances and fuel use for the life cycle of the WPC pallet (one trip of reference flow) at default utilization capacity of .51.

Transit Description	Vehicle Used	Distance	Diesel Used	Source
Unrecovered CDW to Recycling Plant	GLO: Truck, Euro 3, up to 7,5t gross weight / 2,7t payload capacity ts <u-so>	100 km	0.2 kg	[70]
CDW Waste to Extrusion Plant	GLO: Truck, Euro 3, up to 7,5t gross weight / 2,7t payload capacity ts <u-so>	300 km	1.4 kg	[70]
Finished Pallet to Pallet Pooler	GLO: Truck, Euro 3, 12 - 14t gross weight / 9,3t payload capacity ts <u-so>	50 km	.3 kg	[70]
Pallet Pooler to Customer	GLO: Truck, Euro 3, 12 - 14t gross weight / 9,3t payload capacity ts <u-so>	200 km	1.1 kg	[70]
Customer to Store Front	GLO: Truck, Euro 3, 12 - 14t gross weight / 9,3t payload capacity ts <u-so>	40 km	0.2 kg	[70]
Pallet Pooler to EOL	GLO: Truck, Euro 3, up to 7,5t gross weight / 2,7t payload capacity ts	100 km	1.6 kg	[70]

End of Life: The EoL process modeled in this thesis is incineration. To better capture the GWP from the incineration process, separate unit processes were used to individually model the incineration of the wood and plastic fraction. Table 22 shows the LCI data from both processes. The Gabi incineration unit processes [70] are based on an average European waste-to-energy (WtE) plant. The plant has an incineration line fitted with a grate and steam generator with and average efficiency of steam production of 81.9%. The steam is used to produce electricity or exported as heat. Per ton of MSW, 1.09GJ of electricity and 3.16GJ of thermal energy can be produced and distributed to the surrounding customers with a European average grid loss of 7%. The Gabi documentation for the unit process [70] states that "*all utilities used in the waste incineration plant, the operation of the underground deposit and the landfill for bottom ash and air pollution control (APC) residues as well as the meltdown processes for the recovered metals are included in the system.*" The unit process models the replacement of energy and heat produced from a standard EU-28 grid mix which is, 32% nuclear, 19% hard coal, 17% natural gas, 11% lignite, 10% hydro, 6% fuel oil, 5% other, for energy and (40% Natural gas, 34% hard coal, 10% Biomass, 7% lignite, 6% fuel oil, 3% peat) for heat generation.

Table 22.LCI data for waste incineration processes (WPC pallet).

EU-28: Waste incineration of plastics	Unit	Amount	Source
Inputs			
Packaging waste (plastic) [Consumer waste]	kg	58.1	[70]
Outputs			[70]
Carbon dioxide [Inorganic emissions to air]	kg	59.4	[70]
Methane [Organic emissions to air (group VOC)]	kg	-0.3	[70]
Nitrous oxide (laughing gas) [Inorganic emissions to air]	kg	0.0	[70]
EU-28: Waste incineration of wood products	**Unit**	**Amount**	**Source**
Inputs			
Wood waste (For incineration) [Waste for disposal]	kg	207.8	[70]
Outputs			
Carbon dioxide [Inorganic emissions to air]	kg	-101.0	[70]
Carbon dioxide (biotic) [Inorganic emissions to air]	kg	223.7	[70]
Methane [Organic emissions to air (group VOC)]	kg	-0.2	[70]
Nitrous oxide (laughing gas) [Inorganic emissions to air]	kg	0.0	[70]

3.1.2.2 Wooden Pallet

Raw Material Acquisition: Data for the upstream timber production was taken from [71], which is an environmental product declaration of Swedish sawn dried spruce timber. The scope of the study included harvesting, transportation, and manufacturing of the timber. The resulting GWP data was used to model the environmental impacts of upstream timber processing for the wood pallets. Additional information on what is included and excluded from the upstream activities can be seen in the index.

Table 23. LCI data for the upstream timber production process (wood pallet).

Upstream Timber Production	Unit	Amount	Source
Inputs			
Softwood lumber	m3	1.4	[71], Estimated
Outputs			
Carbon dioxide (biotic) [Inorganic emissions to air]	kg	150	[71]
Softwood lumber [Materials from renewable raw materials]	m3	1.4	
Carbon dioxide (land use change) [Inorganic emissions to air]	kg	0.7	[71]
Carbon dioxide [Inorganic emissions to air] Fossil	kg	44.7	[71]

Production: The production process is comprised of the manufacturing of the wooden pallets and the IPSM 15 measures. In order to be shipped across borders the pallets need to undergo a heat treatment process to be compliant with IPSM 15. This LCA considers conventional heat treatment, meaning that the pallet has to be heated to a core temperature of 56 °C for a minimum of 30 mins. A kiln dryer is used in the heat-treating process. [31] The majority of companies that heat treat pallets use natural gas, propane, or fuel as a heat source. The LCI results for the production unit processes can be seen in Table 24 and Table 25.

Table 24. LCI data for pallet manufacturing (wood pallet).

Manufacturing Wood Pallets	Unit	Amount	Source
Inputs			
Thermal energy (MJ) [Thermal energy]	MJ	16.8	[54]
Electricity [Electric power]	MJ	12.6	[54]
Steel billet (St) [Metals]	kg	5.0	[54]
Exterior paint [Minerals]	kg	2.4	[54]
Softwood lumber [Materials from renewable raw materials]	m3	1.4	[54]
Cardboard (packaging) [Materials from renewable raw materials]	kg	1.4	[54]
Outputs			
Wooden pallets (EURO; 40% moisture)	kg	595.0	[54]

Table 25.LCI data for the IPSM 15 treatment process (wood pallets)

IPSM 15 Treatment	Unit	Amount	Source
Inputs			
Wooden pallets (EURO; 40% moisture)	kg	595.0	[31]
Propane [Organic intermediate products]	kg	2.2	[31]
Outputs			
Wooden pallets (EURO; 40% moisture)	kg	595.0	[31]
Carbon dioxide, fossil	kg	6.6	[31]

Use: The use process for the wooden pallet follows the same general path as the WPC pallet. The finished pallet is transported to the pallet pooling company, where the pallet is inserted into the customer's supply chain, loaded with a good or item, and sent to the customer store front. The transportation distances, corresponding fuel use, and trucks are shown in Table 26.

Table 26. Transportation distances and fuel use for the life cycle of the wood pallet (one trip of reference flow).

Transit Description	Vehicle Used	Distance	Diesel Used	Source
Finished Pallet to Pallet Pooler	GLO: Truck, Euro 3, 12 - 14t gross weight / 9,3t payload capacity ts <u-so>	50 km	0.6 kg	[70]
Pallet Pooler to Customer	GLO: Truck, Euro 3, 12 - 14t gross weight / 9,3t payload capacity ts <u-so>	200 km	3.0 kg	[70]
Customer to Store Front	GLO: Truck, Euro 3, 12 - 14t gross weight / 9,3t payload capacity ts <u-so>	40 km	0.7 kg	[70]
Pallet Pooler to EOL	GLO: Truck, Euro 3, up to 7,5t gross weight / 2,7t payload capacity ts <u-so>	100 km	4.7 kg	[70]

End of Life: Similarly, to the WPC pallet, the end of life waste to energy scenario is modeled with the Gabi unit process [70] *"EU-28:Waste Incineration of Wood Products*". The LCI is shown in Table 27. The energy and heat production information is the same as listed in the end of life section for the WPC pallet.

Table 27. LCI data for incineration of wood products (wooden pallet)

EU-28: Waste incineration of wood products	**Unit**	**Amount**	**Source**
Inputs			
Wooden pallets (EURO; 40% moisture) [Materials from renewable raw materials]	kg	595.0	[70]
Outputs			
Carbon dioxide [Inorganic emissions to air]	kg	-440.0	[70]
Carbon dioxide (biotic) [Inorganic emissions to air]	kg	971	[70]
Methane [Organic emissions to air (group VOC)]	kg	-1.1	[70]
Nitrous oxide (laughing gas) [Inorganic emissions to air]	kg	0.0	[70]

3.2 Economic Assessment

As both pallet systems involve different stakeholders, see Table 28, a traditional economic assessment, like life cycle costing (LCC), is a challenge. Aggregating the costs of each pallet system to a single discounted cashflow only tells half of the story, so to speak. The total cost of the pallet is born by different actors in the system. For example, the costs incurred by the pallet producer are not shared by the EoL WtE operators and vice versa. To address this problem, this economic analysis zooms in on a common stakeholder shared by both systems, the pallet pooling company.

Table 28. List of Stakeholders per Pallet System

Stakeholders WPC Pallet	**Stakeholders Wooden Pallet**
Companies Generating CDW	Upstream Timber Gatherers/ Sawmill
Pilot Plant	Pallet Manufacturers
Pallet Pooling Company	Pallet Pooling Company
Pallet Users	Pallet Users
Waste Incineration Operators	Waste Incineration Operators

The pallet pooling company has a choice of what type of pallets to provide for the customer. Pallet material, style, and size all need to be taken into consideration. While it should be acknowledged that different industries require different pallet standards and functions, this CBA assumes that the pallet providing company has a choice to supply wood pallets or WPC pallets to a willing customer for 1000 pallet trips. The specifications of the pallets and corresponding reference flow are the same as in the LCA to facilitate comparison.

Supply chains around the world vary in size, distance, and volume of products shipped through the supply line. Therefore, the time it takes to complete 1000 pallet trips is completely dependent on the company's shipping volume, product demand, and number of pallets available in the pallet pool. Because of this, common measurements of financial feasibility, like net present value (NPV) or the economic internal rate of return (EIRR), would require further assumptions. Therefore, the chosen metric to measure the two systems will be cost/ benefit ratio.

Three cost drivers were identified for the pallet pooling company 1) cost of pallet acquisition 2) costs of pallet repair 3) costs of replacing lost/stolen pallets. Equation 1 shows the relationship of the three main cost drivers to the total benefit, which is the profit obtained from the sale of the pallets, or pallet management contract.

$$C/B = \frac{T_a + TC_r + TC_s}{TB} \qquad (2.1)$$

where

C/B= Cost/Benefit
TC_a=Total Cost of Pallet Acquisition
TC_r= Total Cost of Pallet Repair
TCs=Total Cost to Replace Stolen Pallets
TB=Total Benefit

The following assumptions were made

- Capital costs, labor and internal transportation costs were excluded in order to keep the same system boundaries as the LCA
- All costs were converted to the euro in present day value
- The burden of transporting the pallet to the repair/ inspection center falls to the customer

All costing data for the raw materials of the pallets was gathered from secondary sources and are a reflection of market prices. In order to account for uncertainty in pricing three pricing scenarios were run for each cost variable:

- S(a) 1-3 represents three price scenarios for pallet acquisition
- S(r) 1-3 represents three cost scenarios for repair based on handling intensity
- S(t) 1-3 represents three theft scenarios where new pallets would have to be supplied

Once the costing information was established for each variable, all possible cost outcomes for the pallet were calculated. Figure 17 shows the 27 possible cost outcomes for the wood pallet and the WPC pallet.

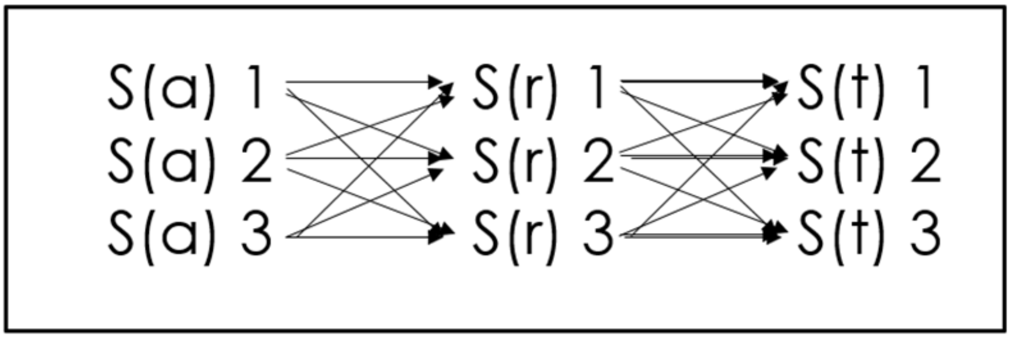

Figure 17. Visual Representation of The Potential Scenario Outcomes

The results were then averaged and the standard deviation was calculated to find the normative distribution, in order to find the costs for each pallet with the highest probability of occurring. Once the most probable cost for the 1000 pallet trips was established, the total benefit was calculated and the resulting C/B ratios for both pallets.

Chapter 4

Results and Discussion

The following sections presents the results of the CBA and the LCA. The results section of the LCA is called LCIA or life cycle impact assessment in order to stay true to LCA form.

4.1 Cost Benefit Analysis

For pallet acquisition, a range of market prices per pallet type were sampled. The results were 15-35 € for heavy duty soft wood pallets and 25-40 € for WPC pallets [63]. TC_a will be represented in 3 scenarios shown in Table 29. S(a) 1 representing the lower end of pallet market cost and S(a)3 representing the higher end of pallet market cost

Table 29. Pallet acquisition costing scenarios for the given reference flow.

Pallet Acquisition Costing Scenario	Wooden Pallet RF	WPC Pallet RF
S(a) 1	€ 180.00	€ 175.00
S(a) 2	€ 240.00	€ 210.00
S(a) 3	€ 300.00	€ 280.00

Pallet repair uncertainties will be modeled in the same fashion as the as the above LCA study. Three repair scenarios are used to illustrate the different handling intensities and levels of repair that a pallet requires throughout its life time. To calculate this, the LCI data from the material cost from the production process was paired with market value material prices, see . and Table 31.

Table 30. Raw material pallet costs for the wooden pallet.

Material Costs Wooden Pallet	Reference	Price of Materials	Cost/reference flow	Source
Virgin Softwood (Finnish Spruce)	Euro/m3	€ 60.00	€ 62.76	[72]
Paint	Euro/liter	€ 10.50	€ 17.64	Estimated
Nails	Euro/ton	€ 500.00	€ 1.50	[73]
Total Cost of the Reference Flow			€ 81.99	

Table 31. Raw material costs for the WPC pallet.

Material Costs (WPC)	Reference	Price	Cost/Reference Flow	Source
Recycled Plastic	Euro/ton	€ 162.40	€ 9.76	[74]
Recovered Wood	Euro/ton	€ 49.88	€ 9.44	[74]
Lubricant	Euro/ton	€ 2,500.00	€ 14.70	[50]
MaPP	Euro/ton	€ 2,500.00	€ 14.70	[50]
Nails	Euro/ton	€ 500.00	€ 1.09	[73]
Total Material Cost of the Reference Flow			€ 49.69	

Once prices were assigned to the costs of production, costs of repair could be estimated in three scenarios. S(r) 1 represents the light repair scenario where 15% of the repaired pallet comes from new material. S(r) 2 represents a scenario where the pallet was handled with moderate intensity and 30% of the repair required comes from new material and S(r) 3 represents a high handling intensity scenario where 40% of the material used for repair is new. The pallet repair scenarios can be seen in Table 32.

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Table 32. Pallet repair cost scenarios.

Pallet Repair Cost Scenario	Wooden Pallet	WPC Pallet
S(r) 1	€ 12.30	€ 7.45
S(r) 2	€ 24.60	€ 14.91
S(r) 3	€ 32.80	€ 19.87

The wooden pallet expert consulted for this thesis, Dan Dillion, mentioned that pallet theft was something that the pallet industry struggled against [63]. As the duration it takes to carry out the reference flow is unknown, the risk level of theft is unknown as well. To model the possibility of pallet theft three more scenarios are modeled. In S(t)1 no pallets are stolen, S(t)2 one pallet is stolen and needs to be replaced and in S(t) 3 two pallets are stolen and need to be replaced. The costs were calculated from the S(a) 2 market costs. The three scenarios modeling the costs of replacing stolen pallets can be seen in Table 33.

Table 33. Pallet theft cost scenario.

Pallet theft Scenario	Wooden Pallet	WPC Pallet
S(t) 1	€ -	€ -
S(t) 2	€ 20.00	€ 30.00
S(t) 3	€ 40.00	€ 60.00

Then, all possible combinations of the three scenario groupings were added together resulting in 27 outcomes per pallet. Figure 18 shows a visual representation of the of the scenario's possibilities. The standard deviation and distribution were then calculated and plotted on a bell curve shown in the results section

As shown in Figure 18, the cost outcome with the highest distribution for the wooden pallet was € 283.13 and for the WPC € 265.56. The total costs differential between the two pallet systems is 17.57€.

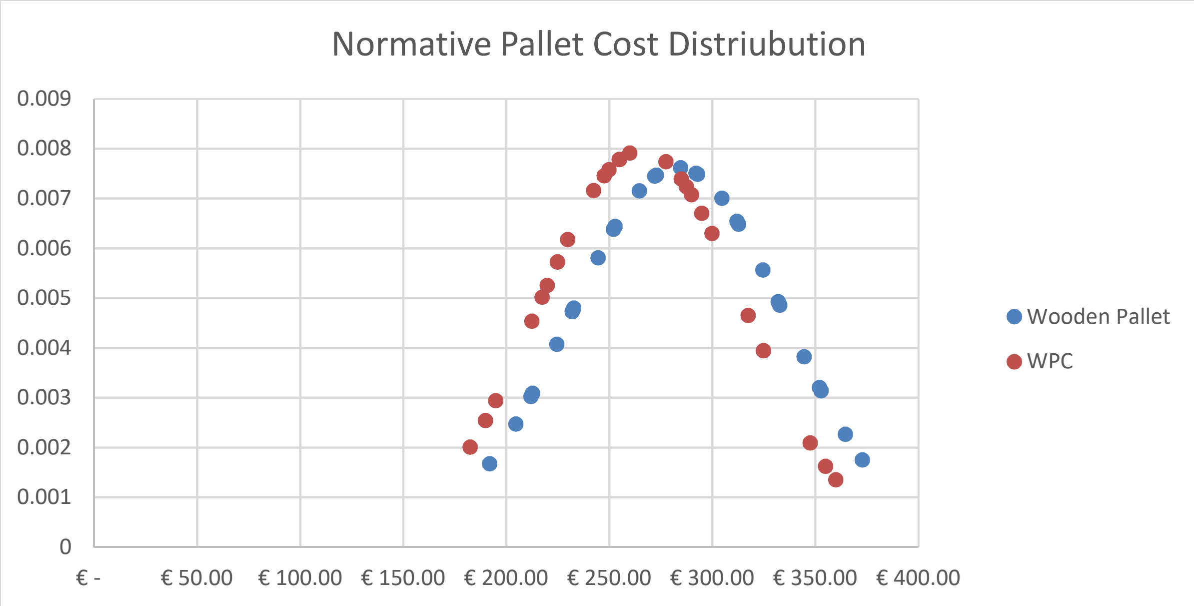

Figure 18. Normal distribution of pallet price scenarios for both the WPC pallet and the wooden pallet.

TB or total benefit refers to the price that the customer is willing to pay for either the wood or the WPC pallets for 1000 trips though their supply chain echelon. The three scenarios described in the above methods section were calculated for each pallet chain. Table 34 shows the price the customer would have to pay for the given reference flow of pallets in order to achieve the desired benefit of a 15%, 20%, and 30% profit margin.

Table 34. Total Benefit Scenarios Reflecting the Price the Customer Would Need to Pay to Achieve a 15% Profit margin, 20% Profit Margin, and a 30% Profit Margin.

Pallet Type	**15%Profit Margin**	**20%Profit Margin**	**30%Profit Margin**
WPC Pallet	€ 305.39	€ 318.67	€ 345.23
Wooden Pallet	€ 325.60	€ 339.76	€ 368.07

Table 35 shows the cost/benefit ratios for the WPC and wood pallets. For the pallet pooling company, the scenario with the lowest C/B ratio is the most profitable. The 30% profit margin scenario has the lowest C/B ratio of 0.77.

Table 35. C/B ratios for each pallet in the three benefit scenarios

Pallet Type	15% Profit Margin C/B	20% Profit Margin	30% Profit Margin
WPC Pallet	0.87	0.83	0.77
Wooden Pallet	0.87	0.83	0.77

Scenario analysis was also used as a type of sensitivity check on the economic data. The multiple scenarios for each costing input were run through a normative distribution to determine, given the uncertainty, which price had the highest statistical possibility of occurring.

The results indicate that, for the given reference flow and variables considered, the WPC pallet is less costly to acquire, repair, and manage for the customer. This is due to the fact that it takes 5 more wooden pallets to complete the 1000 pallet trips than WPC pallet. The resulting benefit for the pallet pooling company is the profit margin gained from sale of the pallets and management services.

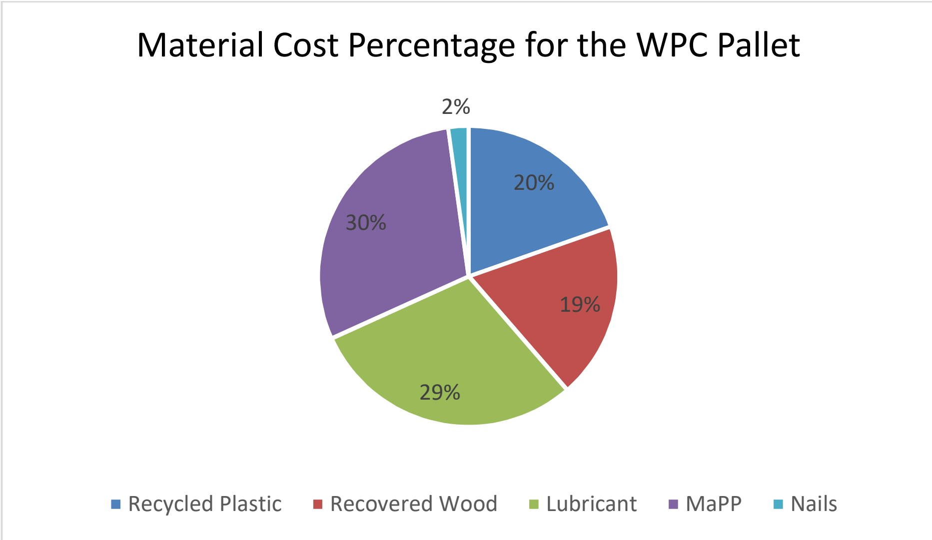

Figure 19. Material cost percentage of WPC pallet.

For the WPC pallet, the costs of lubricant and MAPP were the most expensive. Which accounts for 29% and 30% of the total cost, respectively (see Figure 19).

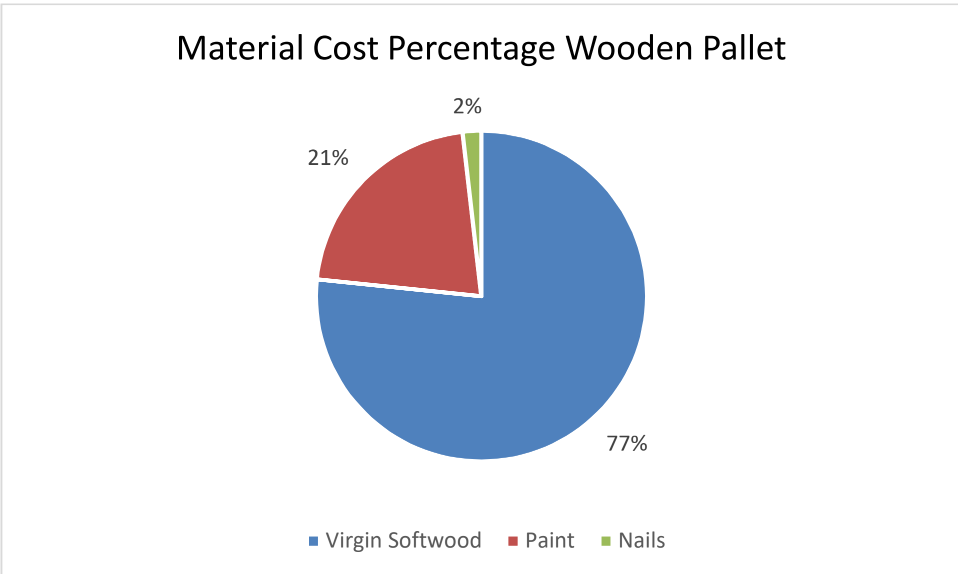

Figure 20. Material cost percentage of wood pallet.

Figure 20 shows the cost percentage breakdown of the wood pallet. The cost of spruce timber is 77% of the total cost of the pallet. The cost/benefit analysis in this thesis was based on the price of raw materials. As such the results are subjected to fluxes in the price of recovered plastic, wood, and virgin pallet timber.

As mentioned in the introduction section on the market forecast of WPC material. The pallet market is expected to grow with a CAGR of 5.3% in Europe. While this market forecasting report did not mention WPC pallets specifically, growth of the WPC market could have a positive impact on WPC pallet producers. The entrance of more firms and producers in the market often leads to novel technological development which could lead to the creation of cost-effective ways to produce, use, and dispose of WPC.

There are a number of factors that were not considered that may have an impact on this result. The electricity cost from the pallet extrusion process was not taken into account, nor were the transportation distances for both the wooden pallet and the WPC pallet. The costs were solely derived from raw material cost. The costing data was sourced from market prices and though scenarios were used as a guard against uncertainty, primary data would paint a more accurate and complete picture for the costs incurred by the pallet pooling company. Furthermore, the pallet poolers proximity to a WPC pallet manufacture could influence the availability and price of the pallets and repair material.

4.2 Life Cycle Impact Assessment

This section presents the results of the LCA. Like the LCI section above, the overall results shown model a high intensity repair scenario.

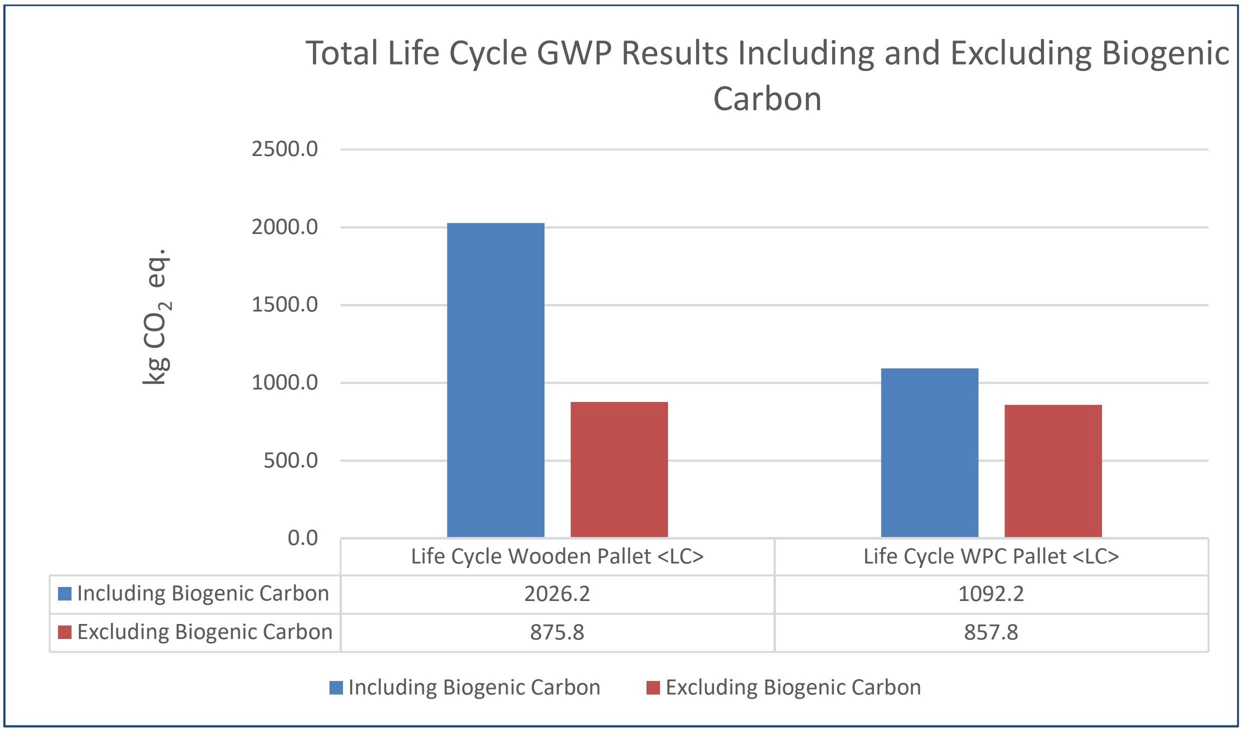

Figure 21. Total GWP Results from both pallet systems (incl. Biogentic Carbon) in kg CO_2 eq, CML 2001-Jan. 2016).

Figure 21 shows the total GWP impact, in kg CO_2, of both pallet systems including and excluding biogenic carbon. Biogenic carbon is the carbon derived from biomass, or matter derived from biological origin [75]. During the lifetime of trees and other organisms made of biomass, carbon is removed from the air via photosynthesis. According to [75] the biogenic carbon content of an item is equal to the amount of carbon removed from the ecosphere during the life of the biomass. The result being, at the EoL stage (once the point of complete oxidation is released) a zero-net sum of CO_2 released. The results including biogenic carbon in Figure 21 count all sources of GHGs as the same, regardless of their emission type (ex. biotic, fossil, land use change). The results excluding biogenic carbon counts CO_2 eq. emissions from biomass as 0. The results show that even when GHG emissions from are excluded, the WPC pallet system has a lower emissions profile for 1000 pallet trips. However, the difference between the two systems when biogenic carbon is excluded is only 18kg of CO_2 eq, which is a reduction of nearly 98% from the results including biogenic carbon.

Figure 22 further explains the above results. The use phase had the highest overall impact on the GWP for both pallet systems. This is due to the amount of diesel consumed by the trucks during the use phase. It takes 5 more wooden pallets to complete 1000 pallet trips which results in a mass differential of 320kg for the refence flow. However, in every other life cycle stage, raw material sourcing, pallet production, and EoL the wooden pallet is more environmentally friendly.

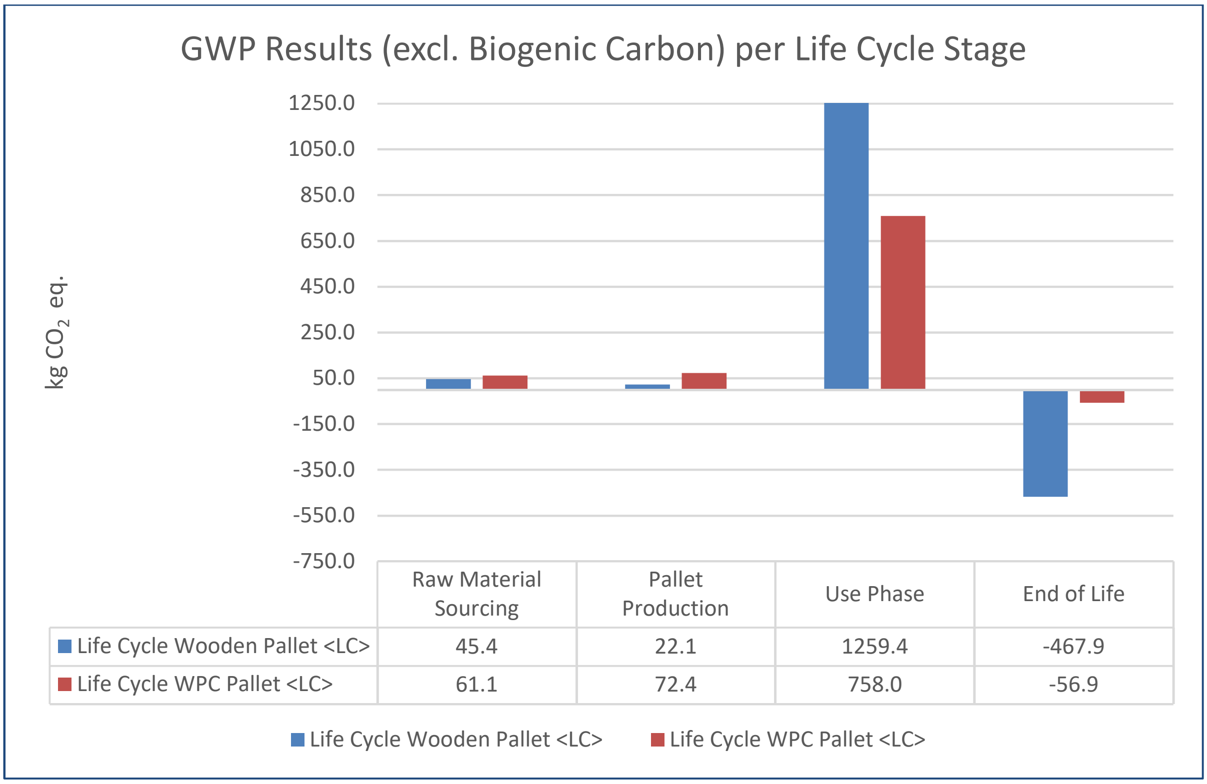

Figure 22. GWP results for 1000 trips of the wood and WPC pallets (excl. biogenic carbon) separated by life cycle stage.

The negative emissions at in the end of life stage are a result of the WtE process and the avoided emissions from using waste to produce heat and energy instead of the average EU-28 grid mix. The Gabi unit process for incineration models the avoided emissions from a standard EU-28 grid mix (for energy this is 32% nuclear, 19% hard coal, 17% natural gas, 11% lignite, 10% hydro, 6% fuel oil, 5% other). In Finland the GWP impact is almost half that of the standard EU-28 as shown in Figure 23. As this project is based in Finland, the GWP results would not offset as many kg of CO_2 eq.

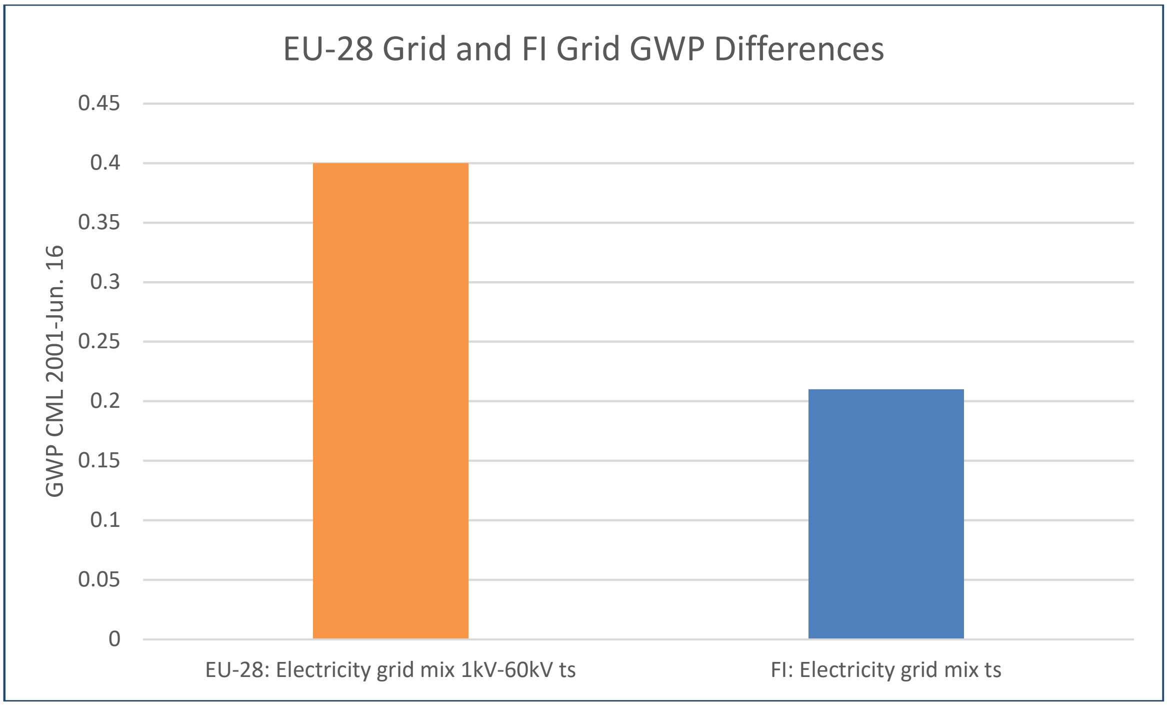

Figure 23. GWP differential between the Finnish grid and the EU-28 average grid mix.

As the use phase is responsible for the majority of the GWP impacts in both pallet life cycles, the transport utilization factor has an impact on the results. The utilization factor is the ratio or load factor based on mass [70]. It describes the relation of transported cargo to the payload capacity. The default utilization setting in Gabi is 0.51, which means the mass of cargo is 51% of the payload capacity. All of the above results were calculated using the default setting. The trucks modeled in Gabi during the use phase are GLO: Truck, Euro 3, 12 - 14t gross weight / 9,3t payload capacity ts <u-so>. A truck this size would have roughly the following dimensions [76];

- length: 5,0 — 8,0 m
- width: 2,4 — 2,5 m
- height: 1,8 — 3,0 m
- volume: 25 — 60 m^3

Figure 24. Visual representation of a 10t eurotruck [76].

During the use phase, the pallets are shipped from the producer to the pallet pooling company. The number of pallets on the truck for that leg of the supply chain will impact the utilization factor. If an average truck volume is taken from the above dimensions, 42.5 m^3, a more accurate utilization factor can be calculated.

$$\frac{Truck\ Volume}{Pallet\ volume} \times \frac{Weight\ of\ pallet\ load}{Payload\ Capacity} = New\ Utilization\ factor \tag{3.1}$$

Table 36. Number of pallets per payload capacity and corresponding utilization factor.

Pallet Material	Volume (m^3)	Weight (kg)	Number of pallets/ Payload	Utilization Factor
WPC	.1	22	307	.69
Wood	.1	34	265	.99

When calculated with a truck volume of 42.5 m^3, the GLO: Truck, Euro 3, 12 - 14t gross weight / 9,3t payload capacity can hold 307 WPC pallets. The volume of wood pallets capable of fitting in the truck is 273 pallets. However, when multiplied by the mass of a wood pallet, the weight exceeds the payload capacity of the truck. The results were then adjusted to the amount of wood pallets that would fit at a .99 utilization capacity, which is 265 pallets as shown in Table 36. The parameter was then changed in the Gabi unit process, and results are shown in Figure 25 For the WPC pallet, there is a 14.3% impact reduction. For the wood pallet the kg CO_2 eq. emissions were reduced by 8.7%.

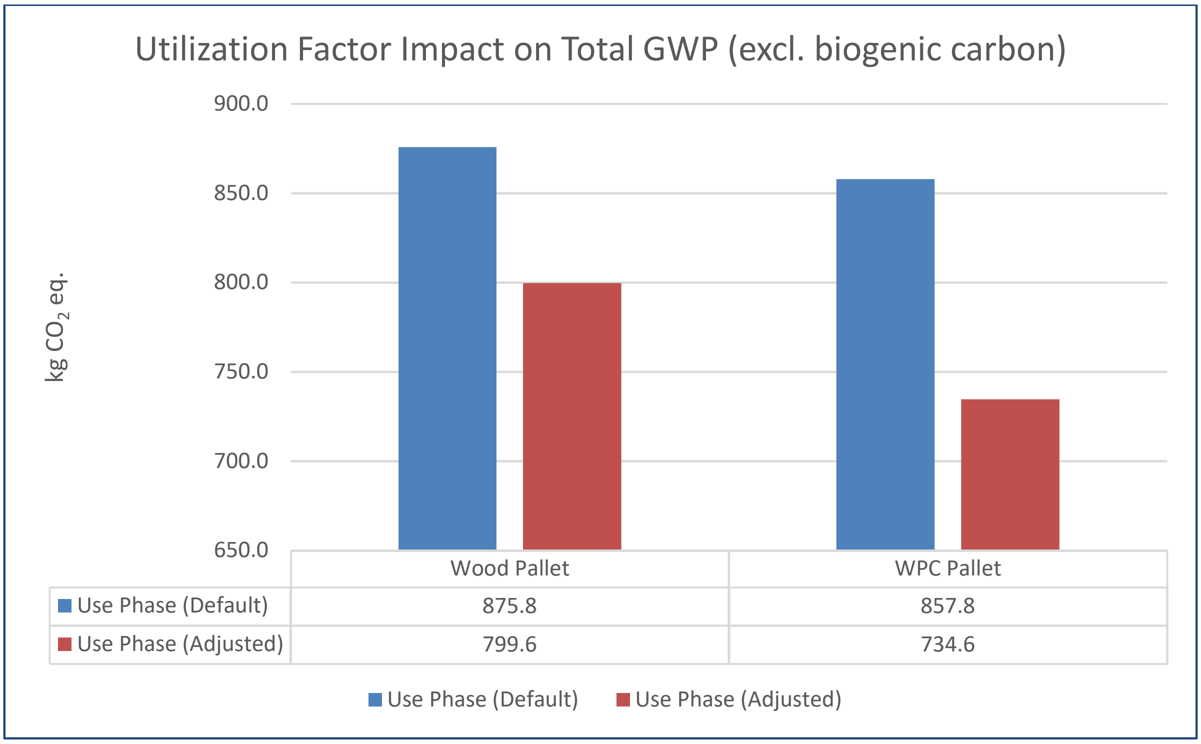

Figure 25. Utilization factor impact on the use life cycle stage of the wood and WPC pallet.

The necessity for pallet repair during the 1000 pallet trips is a source of uncertainty, which is dependent on how the pallet is handled by its users. To account this, three scenarios were modeled for each pallet system. In the high impact handling scenario, 40% total new material is required during the pallet repairs. The medium impact handling scenario requires 30% new material to complete the pallet repairs and the low impact handling scenario requires only 15% new raw material. Figure 26 shows the three possible GWP results for the pallet systems based on the amount of new material needed to repair the pallets for 1000 trips. For the WPC pallets, the more raw material required for repair, the higher the GWP. However, the opposite was true for the WPC pallet. This is due to the emissions offset during the WtE EOL process. As the mass of material increases, so does the amount of thermal energy and electricity generated by incineration, substituting heat and energy production from the EU-28 grid mix. The earlier discussion point about the GWP grid difference between Finland and the EU-28 stands for this graph as well. The results would not be as favorable for the wood pallet-high impact scenario had WtE been used to substitute a Finnish grid and heat mix.

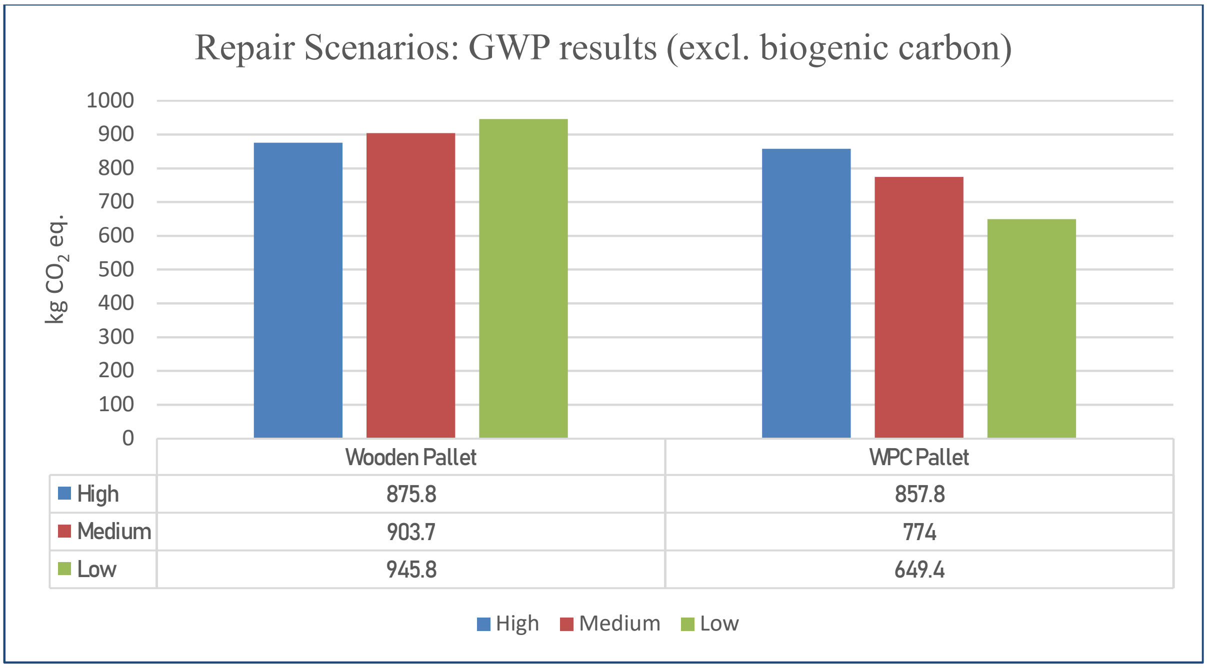

Figure 26. Total life cycle GWP results for three handleing intensity scenarios. High impact requires 40% new material during repair, medium impact requires 30% new material and low impact requires 15% new material.

In the WPC life cycle, the system is expanded to avoid allocation and a recycling scenario was modeled for the unrecovered construction and demolition waste. The use of the unrecovered waste from the WPC pallet life cycle was found to offset 12.8 kg CO_2 eq. emitted by the upstream production processes for virgin glass, steel billet and mineral wool. Other than waste recovery and transportation of the recycling facility, no further processing was taken into account. So, while the results are encouraging, they do not represent the recovery process as a whole.

As the all data for both product systems was found and calculated from secondary sources, the data is neither consistent nor complete. However, as stated in the goal and scope definition, the goal of the thesis is not an absolute declaration as to which product system has a lower GWP result, but rather to illuminate the potential GWP impacts of both systems.

Given the variability of global supply chains and the paths pallets can take through them, the use phase needs to be scrutinized. This LCA models only one generic supply chain route with abstracted distances. Pallets can be transported on ships, trains, and other vehicles. They could be used locally or circumnavigate the globe. Because of this, many published LCA studies on pallets neglect to model a use phase. If the use phase was excluded in the above results, it is clear that the wooden pallet is more environmentally favorable. Even though it requires 5 more of them to fulfill the functional unit of 1000 pallet trips.

The introduction of an economically viable method for recycling WPC might make CDW based WPC pallets more environmentally competitive. [25] concluded that recycling was the more favorable EoL pathway for WPC. Should the technology be created to cost effectively separate the chemically bonded wood and plastic, it may be possible to keep the material circulating longer before reaching incineration.

4.3 Recommendations and Conclusion

The results from the cost/benefit analysis and the LCA indicate that for 1000 pallet trips the WPC pallet is not only cheaper to acquire, manage, and repair but also has less of an impact on the GWP. However, the wood pallet was more environmentally friendly during the other life cycle stages. This is due to the fact that in order to fulfill the 1000 pallet trips 5 more wooden pallets need to be produced and shipped through the supply chain. This, results in the trucks carrying 320 kg more weight during the use phase and raises the amount of fuel needed to complete the trips.

Both pallets have environmental advantages and disadvantages. The WPC pallet keeps CDW circulating in another life cycle before disposal. It has a longer useful life as a pallet and a lower weight compared to the wood pallet, which can reduce transportation emissions. However, the extrusion process and raw material processing are more energy intensive than the wooden pallet production line. Wood pallets are simpler to produce and have less of a GWP impact on all life cycle stages except the use phase. Due to the fact that the majority of pallets are made from wood, they have the added advantage of industry experience and streamlined production processes. They do not have as long of a useful life as the WPC pallets and have a higher tare weight during transit. If the use phase and biogenic carbon are excluded from the results, the wood pallet has a lower GWP impact. The variability of supply chains and impact the utilization factor had of the results, lends itself to the conclusion that the wood pallet is environmentally superior.

Further research needs to be conducted, ideally with primary data from a wooden pallet manufacturing company in Finland and the WPC pilot plant. This would address any gaps in the data and issues with consistency for both the economic data and the LCA data. In order gain a better understanding of the environmental impacts of both pallet systems, an LCA that address more than one impact category would be ideal. Avoided land use could be evaluated to see how utilizing CDW based WPC impacts the felling of trees. If one is to conclude that the wooden pallet is more environmentally favorable, assuring that the wood is sourced from a sustainably managed forest is critical. Abiotic resource depletion could also be evaluated for the pallet systems. Due to the high fuel demand for the use phase, biotic resource depletion may give insight on how fuel consumption impacts the surrounding environment. In a similar vein, the photochemical ozone formation potential could also be evaluated as volatile organic compound (VOC) emissions occur during transit.

The WPC pallets were only compared to one of a few pallet material options. Expanding the scope to include pallets made from virgin plastic, corrugated cardboard, and metal would give a broader perspective on how waste-based WPC pallets stack up against the rest of the industry.

A full financial feasibility study from the perspective of the WPC pilot plant would aid in assessing the economic competitiveness of the WPC pallet. Specific costing data from each stakeholder in the pallets' systems would allow for better insight into a total life CBA.

The LCA results are in line with [61], i.e. for 1000 pallet trips the WPC pallet has a lower GWP impact during the use phase but a higher impact during the production phase. They also concluded that the reduction in GWP emissions during the use phase was a result of the number of useful trips the pallet can make during its lifetime. The study [61], however, did not differentiate between CO_2 emissions from biotic sources and CO_2 emissions from the combustion of fossil fuels. Nor did they model a WtE for an EoL scenario.

Liikanen et al. [22] concluded that the utilizing CDW for WPC production was a more environmentally beneficial option for WPC at EoL when compared to landfilling or incineration. With this in mind, it would be interesting to complete further LCA studies on other potential WPC products produced by the pilot plant. As the pallet industry is dominated by a 90% market share of wood pallets, perhaps using CDW based WPC to produce products in a more competitive market will yield better results.

In the broader context of the circular and bioeconomy, striving for the reuse of waste as new material feedstock and extending product life cycles is a step in the right direction. Though this thesis cannot make any objective claims about which pallet is superior, the results are encouraging for the pilot plant and companies looking at the possibly of CDW utilization in novel ways.

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Table 37. Normative distribution calculation for the WPC and wood pallet.

Standard Div.	Average	Results WPC Pallet	Distribution	Results Wooden Pallet	Distribution	Average	Standard Deviation
50.088837	€ 265.56					€ 283.13	52.34356588
		€ 182.45	0.002010828	€ 192.00	0.00167421		
		€ 212.45	0.004540053	€ 212.00	0.00302705		
		€ 242.45	0.007160693	€ 232.00	0.0047296		
		€ 189.91	0.002545567	€ 204.60	0.0024731		
		€ 219.91	0.005257357	€ 224.60	0.00407856		
		€ 249.91	0.007585051	€ 244.60	0.00581256		
		€ 194.87	0.002942496	€ 212.80	0.00309022		
		€ 224.87	0.0057266	€ 232.80	0.00480019		
		€ 254.87	0.007785488	€ 252.80	0.00644352		
		€ 217.45	0.005021832	€ 252.00	0.00638596		
		€ 247.45	0.007460896	€ 272.00	0.00745114		
		€ 277.45	0.007743331	€ 292.00	0.00751304		
		€ 224.91	0.005729519	€ 264.60	0.00715853		
		€ 254.91	0.007786529	€ 284.60	0.00761862		
		€ 284.91	0.007392268	€ 304.60	0.00700688		
		€ 229.87	0.006179413	€ 272.80	0.00747453		
		€ 259.87	0.007913541	€ 292.80	0.00749274		

		€ 289.87	0.007079501	€ 312.80	0.00649073		
		€ 287.45	0.00723913	€ 312.00	0.00654643		
		€ 317.45	0.004656941	€ 332.00	0.00492935		
		€ 347.45	0.002092778	€ 352.00	0.00320752		
		€ 294.91	0.006708651	€ 324.60	0.00556889		
		€ 324.91	0.003947721	€ 344.60	0.0038248		
		€ 354.91	0.001622803	€ 364.60	0.0022701		
		€ 299.87	0.006298824	€ 332.80	0.00485894		
		€ 324.91	0.003947721	€ 352.80	0.0031433		
		€ 359.87	0.001352963	€ 372.80	0.00175722		

Table 38. System scope of the upstream timber production unit processes.

Upstream Activities	Included in Scope	Excluded in Scope
Raw Material Supply	• Raw material for construction of Sawmill • Raw Material for the construction of vehicles for transport • Extraction of timber-forestry. Including harvesting, thinning, planting, forest roads etc. • Extraction of all other raw materials energy and fuels required in the production of materials consumed in production	• Raw materials to produce chemicals consumed in smaller quantities
Transport	• Transport of timber to sawmills • Transport of Consumables to sawmills • Waste transport vehicles • Internal transit and handling of work machined in the sawmill area	• Personnel transport outside the sawmill area

	• Removal of produced waste	
Manufacturing	• Production of sawed products including barking, sawing drying and sorting was well as packaging	• Personnel space/office or purchase of tools or workwear are not included

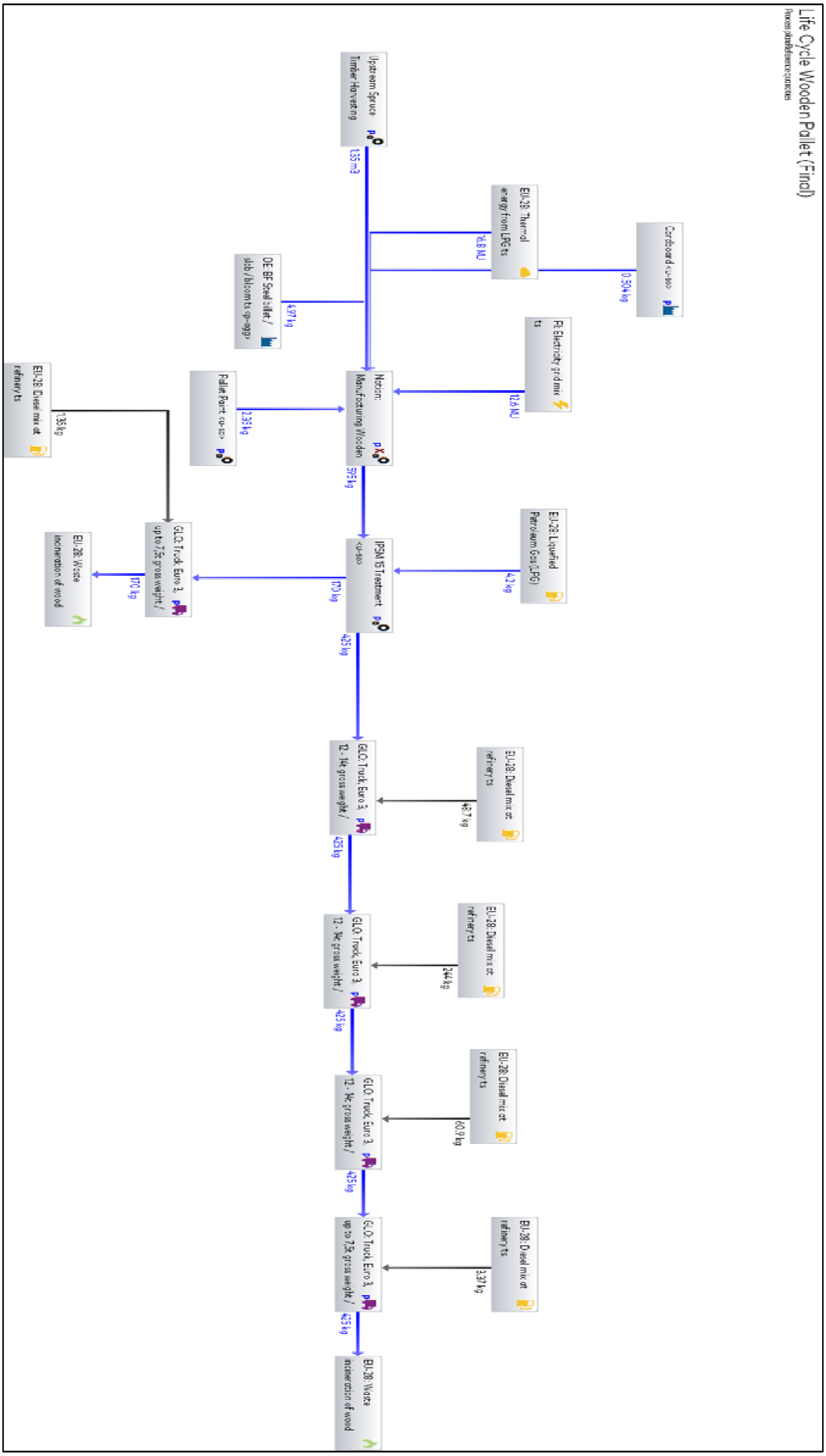

Figure 27. Gabi life cycle model for the wood pallet system.

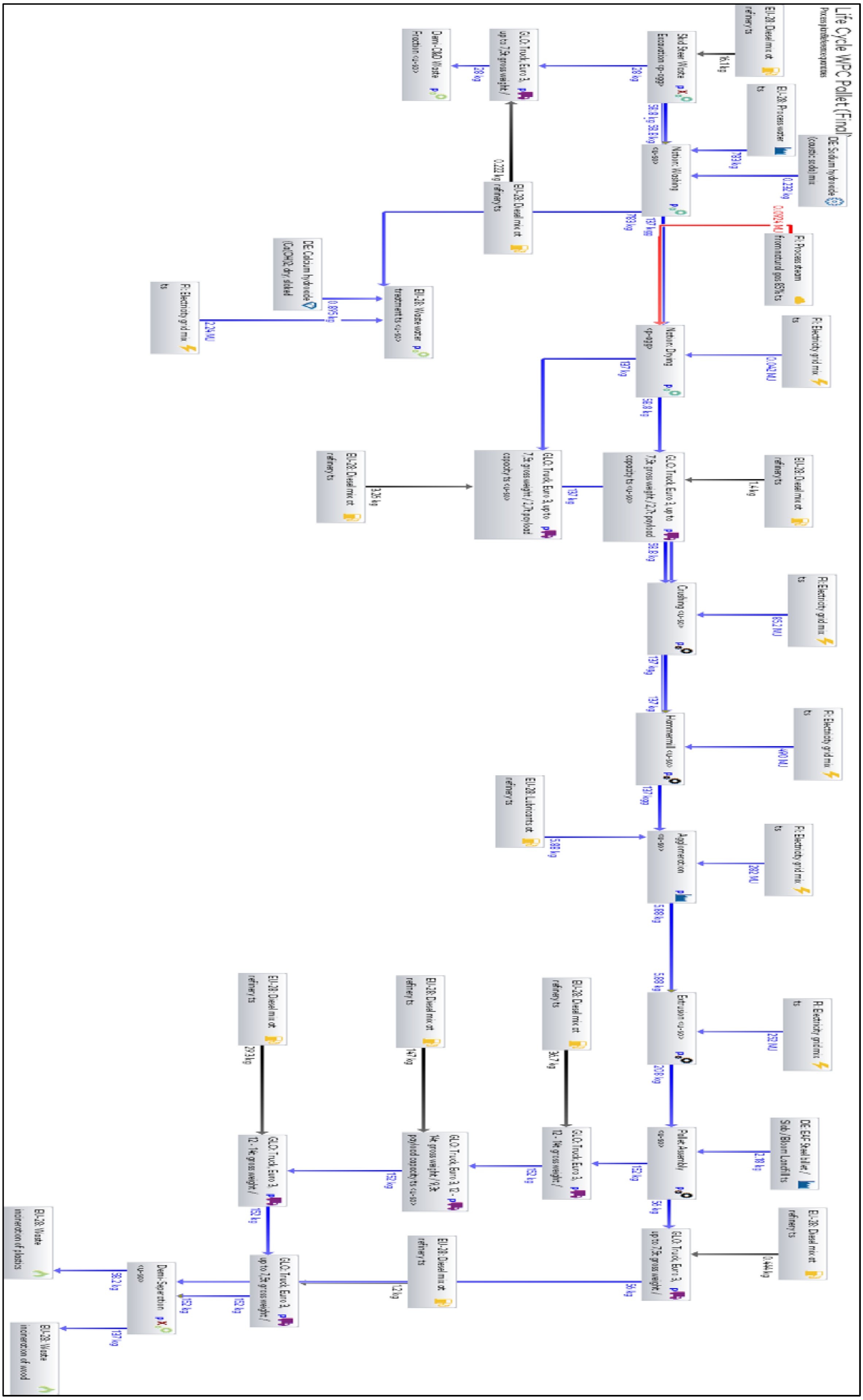

Figure 28. Gabi life cycle model for the WPC pallet system.