Environmental Assessment of the Production and End-of-Life of Cross-Laminated Timber in Western Washington

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Abstract

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Cross-laminated timber (CLT) is a large-scale engineered wood product that may be used as structural components in buildings. Increase in city population leads to higher demand for tall buildings. CLT has the potential of becoming an important alternative material to concrete in an uprising construction industry. The State of Washington is becoming a leader in adopting CLT in the U.S., but research and data at the regional level are lacking, and few studies have considered the impacts of the treatment of CLT at the end of a building's service life. This research developed an environmental assessment to investigate the environmental impacts of CLT over the course of resources extraction, manufacturing, transportation, and end-of-life

(EoL) using life cycle assessment (LCA). The role of facility location and wood species mix involved in the life cycle of CLT are considered. This research also investigated the role of CLT as a construction material in reducing C&D waste in Washington. EoL scenarios are developed based on current waste treatment scenarios in Washington. Important results from this research included: (a) carefully selecting the facilities and wood species can significantly reduce the environmental impacts of CLT production, (b) applying CLT to partially replace concrete and steel in buildings can reduce waste generation associated with C&D, and (c) the environmental impacts associated with CLT at the EoL stage may be significantly reduced when landfill disposal is avoided and that CLT panels are reused. This research contributes references and new knowledge associated with CLT to the construction industry, forestry industry, policy-makers, as well as the academic community, and helps to build a more resilient forest industry.

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Dedication

To my grandma Zhen.

Abbreviations

C&D	Construction and Demolition
CLT	Cross Laminated Timber
EWP	Engineered Wood Product
EoL	End-of-Life
GHG	Greenhouse Gas
GWB	Gypsum Wallboard
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LFG	Landfill Gas
PUR	Polyurethane Resin
SG	Specific Gravity
WTE	Waste-to-Energy

Chapter 1: Background, Literature Review, and Methodology Applied

This chapter provides an overview and literature reviews on the topics covered in this dissertation. Background on the forestry, wood products, and their roles in maintaining the global carbon balance is provided. An outline of this research and its significance and contribution are also given at the end of this chapter.

1.1. Introduction

Climate change continues to be an emerging global concern due to its wide and severe impacts to ecosystem health and human well-being. Many environmental burdens may be attributed to anthropogenic factors. For instance, carbon emissions from vehicles and industrial production are some key pollutant sources from human activities. Some ecosystem damages may be due to natural disturbances, for example, soil erosion, floods, and wild fires. Natural disasters may also be linked to human activities. For example, agricultural expansion requires converting forest lands or grasslands to agricultural lands, causing deforestation and increases the chance of flood and erosion. There are many strategies in response to environmental challenges such as climate change, and among these strategies, reducing carbon emission from industrial, social, and agricultural activities is one of the key focuses for mitigating climate change. Sustainably managing and using available natural resources is a way to reduce human impacts on the environment.

1.1.1. Forests as a Carbon Sink

Forests play an important role in climate change mitigation. Forests account for 31% of the total global land area and provide ecosystem, social, and economic services to many people and other living species. Home to two-thirds of all plants and animals, forests are the most biodiverse terrestrial ecosystems, and about 1.6 billion people around the world on some level depend on forests for livelihood (FAO (Food and Agriculture Organization of the United Nations) 2010), including using forests as a source of food and shelter, cultural practices, medicine, and wood products as a source of income. Not only do forests serve as an important resource to plants, animals, and humans, they also store massive amounts of carbon, one of the constituents of greenhouse gases (GHGs) attributing to climate change, through carbon sequestration. Forest carbon sequestration refers to the process which trees and vegetation uptake atmospheric carbon and store it in the biomass. As a part of the biochemical carbon cycle, forests serve as an important carbon sink and store approximately 289 Gt of carbon in living biomass, accounting for 45% of terrestrial carbon (Bonan 2008). Forests mainly sequester carbon through photosynthesis, and since forest vegetation has the function of preventing soil erosion, it also contributes in protecting carbon storage in forest soils.

As of 2012, forest land accounts for 310 million hectares, or 33% of the total land area in the U.S. (Oswalt et al. 2014). Among these forest lands, timber land accounts for 211 million hectares and reserved forests account for 74 million acres. According to the U.S. Forest Services, about 51.4 million acres of forest land coverage exits in the Pacific Northwest (PNW) region, including national forest and purchase units. The Washington's Department of Natural Resources (DNR) indicated that, among the 8.5 million hectares of forests that exist in Washington, 7.3 million hectares are classified as "timberland", meaning these forests can produce 1.4 m^3 or more of volume growth per hectare annually. Western Washington has 3.8 million hectares of timberlands in total and eastern Washington has 2.6 million hectares, including state, federal, local, tribal, and industrial owned timberlands, while the remaining timberlands are dedicated by law to serve purposes other than logging. Due to past logging activities and natural disturbances, about 75% of forests in western Washington are less than 100 years old, indicating many of the forests are used as commercial timberlands to produce lumber and other forest-derived products. These products are important in keeping forests as a key player in the global carbon cycle.

1.2. Wood Products

1.2.1. Wood Products and Carbon

Common strategies for using forests for climate change mitigation include carbon storage within living biomass and extensive carbon storage in wood products (Perez-Garcia et al. 2007). As stated previously, living biomass sequesters carbon through photosynthesis during its life time. However, this carbon is released back into the atmosphere after the plant is dead or when fallen biomass such as leaves and branches decay. Another way to store carbon is using wood products. In general, any material derived from wood that is for commercial use or direct consumption may be referred to as wood product. Some commonly known wood products include fuel woods, pulp and paper, lumber, plywood, wooden crafts, wood-based furniture, and wood-based structural materials for buildings such as panels and boards, etc. Wood product is the dominant product derived from forests and play a key role in storing the carbon sequestered by living biomass. Trees sequester the most carbon during growth, and the carbon accumulation reaches a steady state after the trees reach maturity (Lippke et al. 2011; Malmsheimer et al. 2008). If the trees are not harvested, their carbon sequestration capacity is significantly reduced while fallen biomass such as leaves and branches release carbon back to the atmosphere. Because of these reasons, sustainably managing forests for commercial use is necessary for extending the carbon storage life time of trees since carbon continues to be stored during the life time of wood products. In other words, if the trees that are harvested to manufacture wood products are replaced by newly planted trees in managed forests, carbon accumulation would continue in the new trees while the carbon sequestered by trees from previous generations is stored in wood products increases the total carbon accumulation over time. Lippke et al. (2011) illustrated this phenomenon in the graph shown below (Figure 1.1). However, it is also important to note that, this phenomenon is applicable to new and secondary forests, but not necessarily to old-growth primary forests due to their significant role in providing ecosystem services and long-standing role as global carbon sinks.

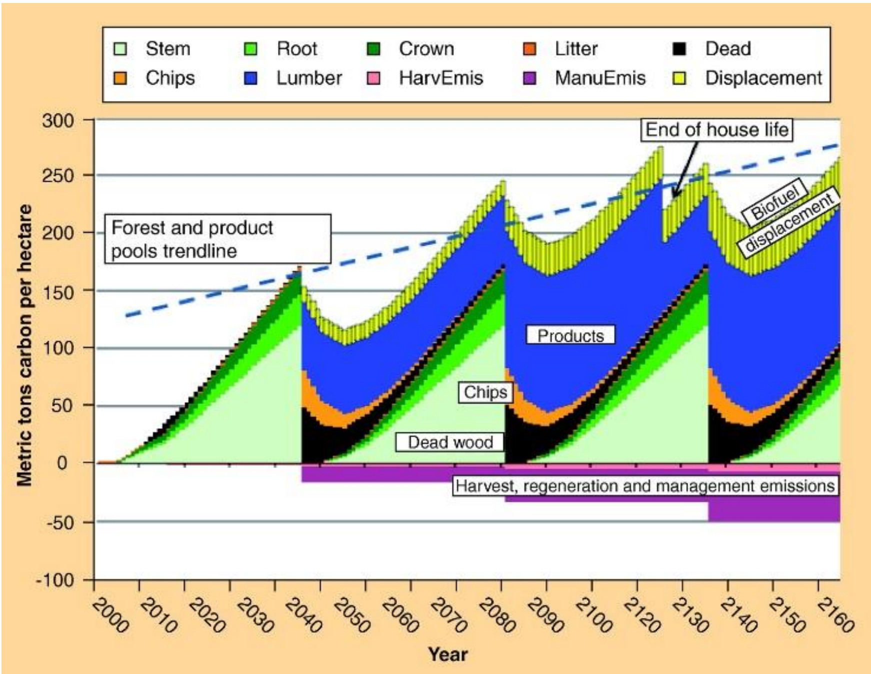


Figure 1.1. Forest plus product-carbon pools and process-energy emissions (Lippke et al. 2011)

Wood products are considered to be low-impact products due to carbon neutrality, meaning carbon emitted by wood is assumed to be biogenic in contrast to fossil carbon. Biogenic carbon emissions, as defined by the EPA, are carbon emissions associated with the natural carbon cycle, as well as emissions from the combustion, processing, fermentation, decomposition, or harvest of biological-based materials. While fossil carbon is associated with the release of CO_2 from the combustion of coal, natural gas, and petroleum, the release of CO_2 associated with the burning of biomass is classified as biogenic carbon, which is offset by the carbon sequestered in newly planted trees. Biogenic carbon associated with wood products may come from several sources: the decay or burning of post-harvest residues, the consumption of biological-based fuels during different life cycle stages, and the release of carbon after the products are landfilled at the end-of-life stage. Because much of the energy for wood products manufacturing comes from the burning of biomass, such as post-harvest or mill residues, biogenic carbon is the primary emission (Puettmann and Wilson 2007). Thus, it is necessary to include biogenic carbon when evaluating the total carbon emissions of wood products.

Carbon storage, as mentioned previously, is an important feature of wood products. Carbon storage in wood products has been considered a way to postpone GHG emissions and increase total carbon accumulation over time. The influences of carbon storage on carbon balance vary depending on the lifetime of products, end-of-life treatments, and forest dynamics. Although the carbon storage in wood products is not permanent, it should be included when estimating the overall carbon pool (Sathre and O'Connor 2010a). Since the carbon stored in wood products is not permanent, substitution of wood-based bioenergy for fossil fuels and fossil-intensive products are considered more significant in terms of the amount of carbon removed from the atmosphere because sustainably managed forests will continue to sequester carbon as carbon contents remain in the wood products (Buchanan and Levine 1999; Sathre and O'Connor 2010b). But for larger dimension wood products such as CLT, the carbon content stored increases compared to other wood products due to its higher mass (Karacabeyli and Douglas

2013). Carbon storage may be a beneficial feature of long-lived wood products, it does not imply that they are "zero emission" since the production of wood products involves various phases that generate emission, even though the emissions from these phases can be offset through biofuel substitution and carbon storage within the wood products Emissions from these phases, such as product handling and transportation associated with wood products, need to be considered to understand the efficiency of using wood.

The time interval of the stored carbon depends on the lifetime of the wood products. In Washington, timber is usually consumed by regional sawmills to produce lumber and construction materials, which are referred to as long-lived wood products. Wood products influence the carbon balance through substitution effects, which includes fuel substitution and material substitution (Knauf et al. 2015). In construction, wood-based materials can serve as an alternative to steel and concrete, from small components such as doors and windows, to larger housing components such as flooring, wall frames, or the entire building structure. The role of wood construction materials in reducing carbon emissions and energy consumptions has been well studied (Lippke et al. 2010, 2004; Bergman et al. 2014; Puettmann and Wilson 2007; Wilson and Dancer 2007). Lippke et al. (2004) compared the environmental performance of houses with and without wood substitution and found that substitution of wood-based bioenergy in wood-frame houses led to significant reduction in non-bioenergy consumption. While carbon stored in wood products is not permanent, emissions avoided or reduced by substituting bioenergy for fossil fuels is forever (Schlamadinger and Marland 1996). Sathre and O'Connor (2010b) provided a meta-analysis for substitution effects of wood products and quantified the

GHG emission reduction of wood substitution. Studies associated with wood products are discussed in detail in the "literature review" section.

1.2.2. Engineered Wood Products

One of the research emphases among the wood product sector is Engineered Wood Products (EWPs), which are composite materials formed by wood particles, boards, or veneers that are bound together using adhesives. EWPs are widely adopted within the construction industry and have many advantages over traditional solid wood in terms of strength, reduced weight, fire resistance, and material uniformity. These advantages allowed EWPs to meet the complexity and higher standards of contemporary constructions. To provide a better understanding of the EWPs currently available in the construction sector, Table 1.1 presents a brief description of some of the most common products.

The timber industry has always had an important place throughout Washington's history, but due to many global and regional social, economic, and environmental factors, the industry has experienced major recessions over the years. For example, when oriented strand board (OSB) became popular, the shift from softwood plywood made exclusively from Douglas-fir to veneer logs from southern pine, which grows at a faster rate and requires shorter rotation time, has caused Washington to lose many of its plywood manufacturers. Moreover, the housing market has experienced some recessions due to the economic slowdowns, which have also impacted the timber industry. But as new technologies have emerged, they have allowed timber products to be used at a scale that was not attainable before. The potential of using wood products in a more efficient way would suggest a higher rate of adoption in the construction industry (Ramage et al. 2017). Higher demand for wood-based products in the construction sector can trigger the introduction of new materials such as cross-laminated timber (CLT).

Table 1.1. Characteristics and applications of common engineered wood products

Product	Characteristics	Common Applications	Other Features	
Plywood	Bonded sheets of veneer with strong adhesives	Wall and roof sheathing, insulation panels, single-layer flooring, etc.	Original engineered wood products	
Oriented Strand Board (OSB)	Rectangularly shaped wood strands, cross-oriented layers, bonded using adhesives	Subflooring, sheathing, webs for I-joists, furniture, etc.	Water-proof, light weight	
Glued-laminated Timbers (Glulam)	Stress-rated wood beam composed of wood laminations, bonded by adhesives	Beams and headers, utility poles, etc.	Stronger, moisture-resistance	
I-Joist	I-shaped, consists of top and bottom flange made of LVL that are connected by OSB web	Residential flooring and roof framing		
Laminated Veneer Lumber (LVL)	Bonded thin veneers using adhesives, grains parallel to the long side	Headers and beam, rims, etc.	Uniform, similar to plywood	

1.3. Cross-Laminated Timber

Originally developed in Austria in the early 1990s, cross-laminated timber (CLT) is a type of large-scale and lightweight engineered wood panel that is commonly used for walls, floors, and roofs in residential and commercial buildings. CLT consists of several layers of lumber boards that are stacked-glued and pressed together in perpendicular layers to form a solid panel. The typical sizes of CLT panels usually range from 2 to 10 feet (0.6 to 3 m) wide, up to 60 feet (18 m) in length, and up to 20 inches (0.5 m) thick. Compared to traditional wood-based construction materials, CLT is conditionally fire resistance according to experimental fire resistance testing and charring rate studies (Frangi et al. 2009; Klippel and Schmid 2017; Schmid et al. 2010; Osborne et al. 2012). The fire-resistant ability of CLT can be accomplished through “charring” on the exterior of the panel, which is when a charred layer is formed during heat exposure and serves as an insulation to protect the remaining structure of the panel. In addition, CLT has several advantages over other wood materials in terms of physical and mechanical properties. Compared to plywood, CLT is less prone to deformations because the alternate layers of lumber make it strong in both the grain and the cross-grain directions. CLT also has greater consistency compared to solid wood since it is made of layers of lumber that are uniform in size and shape.

A compelling characteristic of CLT, compared to other wood-based materials, is that it can be manufactured using small-diameter trees that are considered to have low or no commercial value. Washington forests contain many small-diameter trees because of their low commercial value and lack of budget to clear them, which become potential hazards as they are vulnerable to wildfires and pest outbreaks. As a result, finding uses for small-diameter trees can be beneficial in maintaining a healthier forest habitat (LeVan-Green and Livingston 2001). Incorporating CLT manufacturing in Washington would open the possibility of using these trees as raw materials and therefore reduce natural disasters and increases ecosystem protection.

The CLT industry has existed mostly in Europe and Australia over the past few decades, and it is considered a relatively new in the North America.

Given Washington’s past experiences and maturity in the timber industry, the state has demonstrated great potential in becoming a leader for embracing CLT in the U.S. The city of

Seattle updated its building code in 2012 to include CLT, and the 2015 International Building Code includes references to CLT construction (International Code Council [ICC] 2015). In 2018, the Washington State Building Code Council (SBCC) approved the code changes to allow the structural use of CLT in buildings of up to 18 stories, making Washington the first U.S. state to incorporate mass timber into its building code. For the forestry sector, innovative engineered wood products, such as LVL and I-joist, have developed a strong presence in the U.S. construction industry. The successful adoption of such engineered woods encouraged the development of new forest products and will give CLT a positive market potential as well (Laguarda Mallo and Espinoza 2015).

Changes in population structure may also trigger the development of CLT in Washington. According to the American Housing Survey (AHS) conducted by the U.S. Census Bureau, the percentage of mid to high-rise residential buildings (buildings with 4 floors or more) has been increasing over the years, especially in the in urban areas with dense population. The increase in higher residential buildings could be driven by many factors, including demographic, socioeconomic, and life-style. Seattle's population structure may be a good representation of demographic status in many large cities. As one of the fastest growing cities in the U.S., Seattle's population has been and will likely to continue to grow rapidly. According to the 2010 census, the average household size in Seattle was 2.06 in 2010 with increasing single-person households, and adults between the ages of 25 and 34 make up a large proportion of Seattle's population. This demographic structure contributes greatly to the demand for more multifamily residential buildings. Moreover, seniors seeking multifamily residences with convenient locations may also contribute to the growing demand for mid to high-rise buildings.

CLT is also efficient in terms of construction time, and therefore reduces energy consumption required for construction projects. Studies have suggested that the time of construction using CLT can be significantly reduced compared to that of concrete construction. Lehmann and Hamilton (2011) highlighted the rapid on-site construction of CLT buildings and concluded that the construction time may be as short as three to four months for buildings up to nine stories. The shorter construction time reduces noise impact and disturbances, on-site accident risks, and the need for construction equipment such as fixed cranes that are required in traditional construction methods (Lehmann 2012). Favorable demand potential and time-saving construction will likely encourage the adoption of CLT in the U.S.

1.3.1. Environmental Aspects of CLT

Because of the emerging concern for reducing GHGs as a component of climate change mitigation, using products that have lower carbon footprints has drawn much attention (Bergman et al. 2014). Carbon footprint refers to the quantity of GHGs, particularly CO_2, released per unit of product during its life cycle (International Organization for Standardization [ISO] 2013). The life cycle impacts of CLT, as well as many other construction materials, can be estimated through supply chain analysis. The supply chain would provide an overview of the material flow and the system processes associated with a product, and it is thus necessary to analyze the environmental impacts resulting from a product using a supply chain analysis.

The supply chain for wood products is composed of a network of forest activities, harvests, processing, and distribution (Ramage et al. 2017). Studies may have slightly different definitions or boundaries for the supply chain depending on research context. Each phase within the supply chain generates a certain amount of CO_2 from fuel consumption and other activities, and it is crucial to determine the amount of emissions resulting from these activities to better understand the possibility and potential to make these processes more environmentally sound. To determine the carbon footprint of a product's supply chain, a life cycle assessment (LCA) may be applied to quantify the emissions that occur during the various life cycle stages of that product.

1.4. Life Cycle Assessment

Life Cycle Assessment (LCA) is a tool for evaluating the environmental aspects of a product throughout its entire life cycle. A product's life cycle stages may include, but are not limited to, raw material extraction, manufacturing/processing, usage, and disposal. The International Organization for Standardization documents ISO 14040 and ISO 14044 provided a standard for conducting LCA, and the specific process for conducting an LCA is described in detail in the methodology section of this chapter.

The environmental impacts of a production or service system are evaluated based on the input and output of energy and materials that occurred at each life cycle stage for a defined functional unit of product. The functional unit is defined as the quantity of the identified function of the product, for example, the production of $1m^3$ of wood. The impacts are quantified and presented using multiple life cycle impact assessment categories, known as LCIA categories. Each impact category is modeled using scientific-based conversion factors known as characterization factors (Curran 2006; Solomon 2007; Stocker 2014). For example, the global warming potential (GWP) is often presented as "CO_2 equivalent", "CO_{2e}", or "CO_2 eq." since the characterization factor for GWP is modeled using CO_2 as the reference gas, meaning that the amount of a substance is converted to an equivalent amount of CO_2 that would produce the same global warming effect. The impacts of a process or system may be modeled at different timeframe with the corresponding characterization factors. The most common timeframe used in current LCAs is 100 years, but 20 and 500-year timeframes may be used as well.

LCA is sometimes criticized for its assumptions toward carbon accounting. LCA considers the carbon emissions associated with fossil fuels during the production system of wood products but does not consider emissions from biological sources. For example, it models the diesel fuel used during the transportation of logs, but not the carbon released from biomass decay. This is because of the assumption of carbon neutrality characteristic of wood, meaning the carbon released during the production or usage phases of wood-based products is absorbed by newly planted trees, given that the forests are sustainably managed.

1.5. End-of-Life Treatment of Wood Products

End-of-life, or EoL, refers to the phase where the service life of a product ends. For construction materials, the end-of-life phase begins when the construction project is demolished. The end-of-life options for construction materials often include recycle, reprocess, reuse, disposal in landfills, or energy recovery (John et al. 2009; Robertson et al. 2012). One of the most common treatments of wood materials is direct burning as fuel; other options include recycling and reprocessing for use as raw materials for products such as pellets, pulp, and composite panels. Wood materials not recycled or reused are transported to landfills and allowed to be naturally decomposed over time or managed to collect gasses and flare them to avoid methane or to produce useful energy from collected gasses. Emissions can occur in any of these end-of-life processes because energy input is required to process, manufacture, and transport the wood materials.

The use phase of a building often accounts for most of the emissions (Junnila et al. 2006; Scheuer et al. 2003) and is not considered in the boundary of measurements because it is not a part of the constructed building. The end-of-life phase of building is rarely taken into account in many LCAs, even though it is more directly linked to the products used in construction. As buildings become increasingly energy efficient, the end-of-life phase may play a more important role in the overall energy consumption of construction projects (Dixit et al. 2012; Sandin et al.2014). As consumption of biomass energy shows growing potential, the recycling and reuse of wood products become more important, and end-of-life options should be taken into account more often in studies associated with construction and building materials (Gustavsson and Sathre 2006; Hafner et al. 2014). Although wood is considered carbon neutral, it does not mean they are “emission-free”. Like any other materials, wood products can emit methane, carbon monoxide and many other substances when they are disposed of in landfills or burned. The amount of emission depends on the types of EoL treatment and it has become increasingly important to understand the potential impacts of wood materials at the EoL stage as wood-based commercial buildings may become a new trend in the future.

Research focusing on the EoL phases of wood products is limited due to various reasons. For example, it is challenging to determine the management schemes in the future and the condition of the materials at EoL. Common waste treatment options used for general wastes may be applied to wood products, including landfilling, incineration, recycling, reuse, biofuel production, etc. EoL options for CLT may be similar to other wood products used in construction, but may be more viable to recycling or reuse due to size and durability. The feasibility of reusing CLT panels as a structural component is not clear, but it may be used as non-structural components such as doors or cabinets. The direct reuse of CLT also limit additional processing and the need to separate adhesives. The outcomes of EoL may be further investigated based on existing EoL practices and by finding specific measures that are suitable for CLT.

1.6. Literature Review

Studies associated with forest and forest products are interdisciplinary and can be classified into many categories. The environmental impacts of wood products and wood-based materials can be evaluated from many different aspects. This section summarizes and discusses existing literatures associated with the objectives of the research, including the environmental aspects of wood products, wood construction materials, and the end-of-life options of building materials.

1.6.1. Forest and Carbon Balance

Forest plays an important role in the carbon cycle through carbon sequestration, and forests can store more carbon compared to agricultural or developed land (Malmsheimer et al. 2008). Forest management practices can directly influence the global carbon balance because of biomass level and land-use change (Bonan 2008). Canadell and Raupach (2008) recommended increases in carbon sequestration through reforestation and reducing deforestation, especially in the tropical regions, but well-directed policies and sustainably produced timber and energy are necessary factors to overcome challenges due to land-use changes because of reforestation.

Johnson et al. (2005) assessed the environmental impacts of forest management activities in the Pacific Northwest and Southeast U.S. and found that diesel-based equipment used for harvesting contribute the most to the overall emission of in-forest activities.

The carbon balance associated with forests may be studied from different approaches. There exist many issues in carbon accounting methods that are widely applied in studies associated with wood products. Foley et al. (2005) and Bonan (2008) suggested that forest dynamics and carbon flux are different between tropical forests and temperate or boreal forests. Guest et al. (2013) developed a carbon accounting method that considers the pulse emission of carbon after carbon storage, and Helin et al. (2013) reviewed the potential impacts of including the forest carbon cycle in LCA studies. Another study by Levasseur et al. (2010) considered the temporal aspects of carbon accounting. In the case of corn ethanol substitution for gasoline, the authors developed an approach referred to as dynamic LCA that considers the timing of emissions and land-use changes. Compare to a traditional LCA approach, the new model indicted higher global warming impact for corn ethanol substitution, which implies that the timing of emissions plays an important role in estimating the impact of land-use change. The study also suggested a negative association between the choice of time horizon and the expected timing of emission, and the fixed time horizon that traditional LCA uses may be problematic since it does not consider the actual time when emissions occur.

However, many of these studies did not target wood products from sustainably managed forest, the most important forest-derived products, and overlooked the role of wood products in reducing carbon emissions. It is necessary to consider the storage effect of wood products to increase the accuracy of estimation and understand the benefits of using woods. The biogenic carbon emitted from wood products, from the manufacturing stage to the disposal stage, were not discussed in these studies. Although forests are a major carbon pool, the role of wood products should not be neglected as they are necessary in helping us understand the environmental impacts associated with forests.

1.6.2. Environmental Aspects of Wood Products

Wood products are widely used in the construction sector. While research associated with the physical properties of wood products determine their usability in construction, research related to the environmental aspects of wood products has developed into an important research area. For example, some researchers are interested in investigating the effects of using wood instead of alternative materials in one or more building component, while some focus on the environmental impacts directly associated with the production and use of wood materials. The following sections provide an overview associated with the environmental aspects of wood products based on currently available research studies.

The substitution effect of wood on the carbon balance can be summarized into several mechanisms, including fossil energy used to manufacture wood products as compared to alternative materials, avoidance of emissions from industrial processes, carbon storage in forests and wood products, using co-products from wood as bioenergy to replace fossil fuels, and possible carbon sequestration and methane emissions from landfills (Sathre and O'Connor 2010a). Wood products are often compared to alternative building materials such as steel and concrete. In a study comparing the energy and carbon balances of wood and concrete building materials in Sweden (Gustavsson and Sathre 2006), the authors calculated the energy input and output for a 4-story apartment building. Impacts of functionally equivalent versions of wall frames using reinforced concrete and wood, particularly plywood and particleboard, were evaluated based on the energy required for material production, residue recovery, and demolition. The study suggested that the overall emission impacts from using a wood frame is lower than using a concrete frame in terms of carbon balance. This is mainly due to fossil fuel replacement by biofuel, the recovery of logging and processing residues, and more importantly, the replacement of fossil-intensive products. Additionally, forests in the proposed study area that are not used for material production are considered "surplus" and are considered to impact the carbon balance depending on the use of these trees. The study included some demolition options for the building materials, but did not account for the impacts of landfilling.

The carbon storage function of wood products has also been studied, including carbon pool changes in terms of land-use changes over time, the value of delaying carbon emission by temporary carbon storage, and the choice of time horizon (Brandão et al. 2013). Perez-Garcia et al. (2007) assessed the carbon pool and storage behavior associated with forest, wood products, and fossil fuel displacement by forest products. The study developed a carbon accounting strategy based on results from a number of LCA studies for estimating the carbon pools and storage in forests and wood products. The model described in this study combined simulations and Landscape Management System to simulate the growth and yield of targeted forests in the Pacific Northwest. The results showed that although forests without logging activities accumulate more carbon compared to those with logging activities, by expanding the system boundary to the product level, higher levels of carbon is accumulated over time, as compared to the case with no logging activities, if the logged trees are manufactured into wood-based products to replace non-wood products, such as in construction projects, given that new trees are generated to replace the logged trees.

Buchanan and Levine (1999) analyzed the role of wood products in terms of carbon storage and energy balance within the building industry in New Zealand. The study estimated the global carbon storage in wood products and calculated the energy and carbon coefficients. These coefficients were used to estimate the carbon implications of building material selection. Depending on the type of buildings (i.e. commercial, industrial, hostel, houses), the authors calculated the energy and carbon contents. The study also acknowledged the substitution effect for replacing materials such as concrete or aluminum with wood and found significant reductions in emissions if typical houses used woods for window frames instead of aluminum. The study also projected a 20% reduction in carbon emissions from building material manufacturing if the country's building industry increased its wood usage by 17%. Increasing the use of wood materials resulted in a 1.8% reduction in total carbon emissions in New Zealand, and 75% of the reduction estimated in the study comes from the replacement of energy intensive products with wood. However, the impacts of fuel substitution and the potential of sustainable forest management were uncertain.

In the U.S., similar studies have been conducted to investigate the energy and emission impacts of using wood products. Lippke et al. (2004) used two residential houses in both warm and cold climate regions to evaluate the environmental performance of buildings that used renewable construction material substitutions. A wood-framed and a steel-framed house were compared in Minneapolis, MN, representing a cold climate region, and a wood-framed and concrete-framed house were compared in Atlanta, GA, representing a warm and humid climate region. The results showed that, based on the analysis of energy consumption, emissions, and carbon storage at each phase throughout the manufacturing and usage of materials, the substitution effects of bioenergy during phases such as material production and construction reduced the overall energy consumption significantly for the wood-framed houses in both regions. This implies that, although the energy consumption for the steel and concrete houses were not much greater compared to the wood-framed houses, when accounting for the bioenergy substitution, the reduction in carbon emission from non-bioenergy for wood-framed houses was significant. An interesting point that this study suggested was that the carbon storage from the wood-framed house in Minneapolis exceeded the emission, but this is not true for the Atlanta house. This may be due to the short forest rotation period in the Southeast, which allows less carbon to sequester. The effects of fuel substitution were compared and indicated significant reduction in energy requirements.

Moreover, Brunet-Navarro et al. (2016) found that increasing the lifespan and recycling rate of wood products may further improve the carbon storage benefits over time and suggested that using long-lived wood products is a good way to increase the carbon storage capacity of woods, which is similar to the conclusions of Lippke et al. (2010). However, the authors acknowledged the model used in the study was simplified and the degradation of recycled products was not considered. Nonetheless, the study made a point in comparing the differences in carbon emissions of extending product lifespan and recycling rate versus the "business as usual" scenario. A similar conclusion can be applied to the U.S. forest sector, where increases in the usage of wood materials in long-lived wood products may reduce carbon emissions

(Bergman et al. 2014; Lippke et al. 2011). The bottom line is that these studies suggested that there is certainly potential in increasing the lifespan and usage of wood products in buildings.

Using wood as a construction material, especially as structural components, extends its carbon benefits because of longer service life. Emissions generated during the production phase of wood products may be offset by using newly planted trees, and by replacing fossil fuels with biomass-based fuels. Over time, carbon sequestered by existing and newly planted trees would offset the emissions associated with the wood product production activities. Adding the carbon credits of the avoided emissions of replacing fossil fuel with biomass-based fuels, the carbon benefit of using wood products would outweigh the emissions.

The use phase of a building plays a significant role in determining the total emissions associated with the life cycle of that building (Buchanan and Levine 1999; Gustavsson et al. 2010; Salazar and Meil 2009). A building requires sufficient amounts of energy to maintain normal building operations, and the energy consumption may be reduced by improving the operating efficiency of buildings. For example, Gustavsson et al. (2010) calculated the primary energy use during the production, service, and end-of-life phase of a wood-framed building, and concluded that, choosing a biomass-based district heating system during the use phase of a building can significantly reduce the CO2 emission of a wood-framed building, and therefore helping to achieve negative CO_2 emission over a building's life cycle.

Increasing the use of wood in buildings has carbon benefits over using conventional materials if carbon storage is considered. It is important to note that the carbon benefits associated with using wood as a construction material depend on many factors involved during the production, use, and disposal phase. Salazar and Meil (2009) compared a wood-intensive house that maximized wood use with a typical house that used more conventional materials (e.g. bricks, asphalt). The results showed that the wood-intensive building can result in a negative net carbon if fossil fuel substitution and landfill gas recovery practices are taken place.

1.6.3. Life Cycle Assessment Approach for Wood Products

Estimating the environmental impacts associated with using wood products may be approached in many ways. LCA is an effective tool in evaluating the environmental impacts of wood products. The benefits of using wood products, as well as woody biomass, as a way of reducing pollutants and emissions have been well studied. Wood products as construction materials have been found to reduce greenhouse gas emissions in many studies among the construction sector, particularly in European countries (Börjesson and Gustavsson 2000; Cabeza et al. 2014; Gustavsson and Sathre 2006; Werner and Richter 2007). LCA studies associated with wood products have been conducted worldwide. For example, Zabalza Bribián et al. (2011) conducted a comparative analysis of the energy requirements between building materials, including bricks, cement, concrete, and wood products using a life cycle assessment approach. However, the study is for comparative purposes and the functional unit was 1 kg of the targeted materials. Thus, the results are not useful when comparing the performance of the materials when they have different physical properties. For example, the function of 1 kg of wood is different from that of 1 kg of concrete.

LCA studies can be used as references when comparing different products. Petersen and Solberg (2005) reviewed the impacts of using wood products based on economic and environmental analyses in Norway and Sweden. According to this overview, the avoided greenhouse gas emissions of using wood products as a substitution for steel and concrete were significant among all studies. From a life cycle assessment perspective, the resulting advantages of using wood products could have been more significant if system boundaries were expanded and in-forest carbon fixation was considered. The authors also suggested the inclusion of the time profile of GHG emissions over the life cycle.

Nebel et al. (2004) conducted life cycle analysis on wood floor coverings in Germany that covered 70% of the country's flooring production. The study included the life cycle stages of wood flooring such as forest management, manufacturing, finishing, and end-of-life. The study considered the impacts of solid parquet of various thicknesses (8 mm, 10 mm, and 22 mm) made of four different tree species and evaluated the environmental performance over a 50-year timeframe. The flooring was assumed to be used for thermal energy at the end of service life. The results indicated that carefully choosing the functional unit and the timeframe is important as they may lead to very different results due to variations in function, maintenance requirement, and refurbishment times. For example, the 22 mm parquets have lower global warming than the 8 mm parquets over a 50-year time frame because the thicker parquets have a longer service life. However, the 22 mm parquets require more repairs in 50 years than if they are used for only 25 years, which in turn, produce higher warming impacts over a longer service life time. These variations implied the uncertainties on questions such as to what extent and how wood should be used and treated in construction projects.

In China, Lun et al. (2016) studied the carbon footprint of different harvested wood products (HWPs) from a type of larch (*Larix principis-rupprechtii*) using a life cycle analysis approach. The authors developed a growth model for biomass estimation based on inventory data and found that 66.2% of the carbon sequestered over one forest rotation period was stored in HWPs after the trees were harvested. Although the manufacturing stage contributes the greatest amount to the carbon footprint, it is still lower than the carbon storage in the HWPs. The study also considered substitution effects of HWPs and wood fuel for fossil fuel replacement. The results indicated that increasing the utilization efficiency of wood fuel can contribute positively to carbon mitigation, and the authors recommended possible extension of wood products lifetime and the recycle/reuse of disposed woods.

In the United States, the impacts of the production processes for wood-based materials such plywood, softwood lumber, engineered wood products such as laminated veneer lumber (LVL) and I-joists are well documented, and LCA has been performed on a series of wood material production processes throughout the country. For instance, the Consortium for Research on Renewable Industrial Materials (CORRIM) has developed and updated inventory data and conducted life cycle analysis for softwood lumber and I-joist production in the northwestern U.S. (Puettmann 2013; Puettmann et al.2010), and it has recently updated its reports for various wood products from its previous studies.

There are four major research phases for the CORRIM studies. Four Special Issues have been published by CORRIM - (1) 2005: life cycle assessments for wood buildings & their structural products produced in the Pacific Northwest (PNW) and Southeast (SE) supply regions (CORRIM 2005); (2) 2010: extensions to the North East/North Central and Inland West supply regions and West Coast seismic building codes plus MDF and Particleboard as high volume non-structural products (CORRIM 2010); (3) 2012: Environmental performance of wood based biofuels (CORRIM 2012); and (4) 2017: an update to the primary survey data collected for these earlier life cycle impact estimates (CORRIM 2017). Hence this research uses recent updates in forest product and region-specific life cycle inventory measures, as provided by many contributing researchers, in order to develop a more integrated perspective of current progress and opportunities to reduce carbon emissions as the leading global environmental concern.

Updates to older CORRIM studies are often provided in more recent reports. For example, the report by Puettmann (2013) on the LCA of I-joists updated the original inventory data in previous studies on sawmill and LVL production processes (Wilson and Dancer 2007) and developed an updated analysis of environmental impacts from I-joist production in the Pacific Northwest. The CORRIM studies reported advantages of wood usage over alternative materials in construction, such as reinforced concrete and steel, due to their renewable characteristic and ability to store carbon. Given that the trees are harvested from sustainably managed forests, carbon released from harvesting and material production is sequestered by newly planted trees, and the carbon that was originally stored in the harvested trees continues to be stored in wood materials during the life time of the building, which is usually assumed to be 80 years or more.

1.6.4. Environmental Impacts of CLT

Compared to wood products such as lumber and plywood, CLT is relatively new and is not often used in the U.S. Nonetheless, CLT related research has been conducted worldwide, especially on the environmental performance of CLT-based mid-rise buildings. As a type of mass timber, CLT can be used for wall frames, floors, and roofs. Higher strength and fire-resistance ability make CLT suitable for use in multi-story buildings. From an environmental aspect, one of the important concerns of using CLT as an alternative material to concrete and steel in construction is its environmental performance in usage. An energy performance analysis was conducted for an eight-story wood-framed building in Sweden (Gustavsson et al. 2010). Although the study did not emphasize CLT, it provided a well-established framework for determining the primary energy use and carbon emissions based on the lifecycle stages of wood-based building materials, from the production to the end-of-life phases. The study suggested that the building operation becomes the dominant consumer of energy as the lifespan of a building increases, and more importantly, biomass-based supply systems play an important part in achieving negative net carbon emissions since biomass, residues and recycled materials may be reused.

In Canada, Robertson et al. (2012) conducted a life cycle analysis for an existing building in British Columbia under an alternative design scenario where glulam and CLT are used. The results of this LCA were compared with those of a traditional reinforced concrete building used for the same study. In this comparative life cycle analysis, the timber-framed building outperformed the concrete building in 10 out of the 11 environmental impact categories assessed in the study, especially in global warming, ozone depletion, human health, and air pollution impacts. This study provided a well-structured description of LCA results for a CLT-glulam hybrid building that emphasized the impacts of the supply chain and accounted for the benefits of carbon storage in wood materials. For whole-building LCAs, it is difficult to compare the results since each case study uses buildings of different size and height. Therefore, considering the impacts of an important component of the building is the key to compare LCA results between case studies. This case study, as defined by the authors, was strictly limited in terms of geographic and temporal scales. A great portion of the data used for the study was secondary data from the Athena life cycle inventory database provided by the Athena Sustainable Materials Institute (ASMI) or small-scale pilot studies, and the assessment did not consider the end-of-life phase of the building, although it was mentioned that there are many possible end-of-life options for the materials.

FPInnovations (Karacabeyli and Douglas 2013) provided preliminary LCA results for a CLT apartment building in Québec, Canada. The study emphasized the overall environmental impacts of CLT buildings assuming different end-of-life and recycling scenarios. An interesting point this study made is that, if CLT is reused for 50% of the building materials and 50% of the materials are recycled at the EoL stage, the avoided emissions from forest regrowth is not as high as the scenarios where no recycled CLT panels are used, but the emissions from landfilling is reduced since half of the demolished materials are recycled or reused. Moreover, by using more recycled panels, the carbon sequestered in non-harvested trees increases assuming they are not used for material production and remain in the forest. However, the study is based on the data provided by the Athena Sustainable Materials Institute, meaning that the results may be very different if assessed in the PNW region of the U.S. due to changes in parameters such as forest location, management scheme, and logistics.

CLT has been gaining more recognition in the U.S. recently. Still, few studies have focused on the environmental aspects of CLT and data associated with the CLT supply chain is very limited. It should be noted that many factors, including policy changes, standard guidelines, market demand, and public awareness may directly influence the CLT supply chain, but few studies have examined the level of influences. For example, the APA (APA-The Engineered

Wood Association) published the performance standards for CLT and provided guidelines for CLT application in the construction industry (APA-The Engineered Wood Association 2012). The document outlined the lumber requirement for different CLT grades, including the wood species mixes that are required for each grade. Changes in parameters related to these standards can influence the impacts generated from CLT production, but no existing literature in the U.S. has discussed these topics in detail.

Another important aspect is the transportation that links together the various phases during production. Lehmann (2012) concluded that the transportation distance can directly influence the carbon benefits of sustainable construction and the materials should be obtained from a nearby source, which implies that the selection of sites can directly affect the environmental value of construction materials. However, the role of transportation is not recognized as a main component in the studies described above. There are few studies that evaluate the impacts of wood products based on changes in transportation logistics. In the case of CLT production, longer hauling distance and more stages of processing involving energy consumption are involved, making the location of facilities more important. The level of impacts associated with such aspects need to be included in CLT studies.

1.6.5. End-of-Life of Wood Materials and CLT

The end-of-life phase of wood materials has been discussed in some of the studies associated with the construction and energy sectors (Dodoo et al. 2009; Gielen 1998; Gustavsson et al. 2010; Lippke and Puettmann 2013; Robertson et al. 2012). Dodoo et al. (2009) compared end-of-life impacts of wood-framed buildings to that of concrete and steel buildings. Concrete is assumed to be either landfilled or crushed into aggregate for carbonation while the wood was assumed to be recovered for energy to replace fossil fuels. Carbonation is a chemical process in which CO_2 in the atmosphere binds with the calcium oxide (CaO) in cement to form calcium carbonate ($CaCO_3$), and therefore reduces GHG. The results of the study showed that although crushed concrete uptakes significant amounts of CO_2, the energy input associated with fossil fuel uses from the post-handling of concrete offsets most of the carbon benefits. On the other hand, by replacing fossil fuels with wood-based bioenergy, the carbon benefits of wood buildings are much greater in comparison.

Lippke and Puettmann (2013) studied the impacts of converting waste wood to energy for use in district heating. The study mostly focused on evaluating the impacts of biomass energy production from a biomass boiler for fossil fuel replacement, but also incorporated alternative options of waste wood usage, including recycle, reprocess, and landfill. Treatments of co-products such as forest and sawmill residuals were also considered. Among the 6 scenarios involving demolition materials, recovering demolition waste woods for reprocessing, reuse, or fossil fuel displacement resulted in higher carbon stocks over time compared to the base case scenario, which involves no demolished material recovery.

End-of-life stage scenarios included in many studies are developed based on previous literature and assumptions which created a number of limitations, and in some studies, the end-of-life options are only discussed rather than actually analyzed. For example, the recovery of wood materials for fuel after demolition are often the most common EoL alternative in existing studies (Gustavsson et al. 2010; Puettmaan and Lippke 2013), but these studies did not go into detail about other treatment options. Some studies considered the recycling option of building materials, but did not consider the processing stages after the materials are transported (Scheuer et al. 2003). Moreover, mass timber such as CLT is unique compared to many other engineered wood products in terms of its physical and structural features. This implies that the potential of reusing CLT may be greater and more feasible compared to other materials. Robertson et al. (2012) discussed the possible end-of-life options for CLT based on treatments for glulam materials. However, the applicability of these treatment scenarios need further investigation since glulam is different from CLT. For CLT, it could be possible to take entire components for resell or reuse in another project. If this is the case, the total environmental impact from processing recyclable parts could be significantly reduced.

There are some data associated with the EoL of CLT outside of the U.S., mostly from environmental declarations of CLT products (Cross Timber System Ltd. 2016). Literature that provides emphasis on the EoL impacts of CLT panels is still very limited. Some studies excluded the EoL phase and some assumed relatively extreme cases for CLT disposal (e.g. 100% landfill). This could be due to limitations of available data and uncertainties in future treatment of CLT. For instance, Durlinger et al. (2013) conducted a whole-building life cycle analysis for a CLT building in Australia and included EoL analysis of CLT materials. However, only the landfill option was considered in this study. An analysis associated with the degradation of CLT in landfills was also mentioned in Durlinger et al. (2013). Degradable organic carbon was considered and the results suggested that degradation values used were not significant in influencing the total GHG emission. Nonetheless, due to the lack of evidence of the EoL fate of CLT, the EoL results provided in this study were not clear and actual emissions of methane was not mentioned.

Liu et al. (2016) assessed the impacts of using CLT as an alternative material to concrete and steel in buildings in two provinces in China. The study included the end-of-life stage where the materials are landfilled, recycled, or reused. All concrete and steel materials are landfilled after demolition while 55% of the materials from the CLT building were recycled with 45% used for energy. As a result, the carbon emission and energy consumption in the CLT buildings were lower compared to the concrete buildings in both provinces. The operation stage accounted for 80% of the total carbon emission of each building, but the CLT buildings require less energy for heating and therefore had lower energy consumption compared to the concrete buildings. The study did not discuss much detail about the EoL phase, but suggested that the carbon emissions for CLT buildings were offset by recycling CLT materials. Although the study provided a cradle-to-grave LCA analysis, it did not discuss any emissions associated with landfilling and burning beyond CO_2.

1.7. Life Cycle Assessment Methodology

This section provides an overview of LCA terms and methodology. LCA is a tool for evaluating the environmental aspects of a product throughout its entire life cycle. A product's life cycle stages may include raw material extraction, manufacturing/processing, usage, and disposal. LCA is generally based on the standards provided by ISO 14040 and ISO 14044 (ISO 2006a; ISO 2006b). Several required phases are included in the LCA model based on these standards (Figure 1.2): goal and scope definition, inventory analysis, impact assessment, and interpretation. Since this study is more regional-specific and requires intensive data, additional steps will be required to conduct impact analysis. This section describes the LCA method that will be incorporated into the CLT supply chain analysis and provides detail about the steps for analysis.

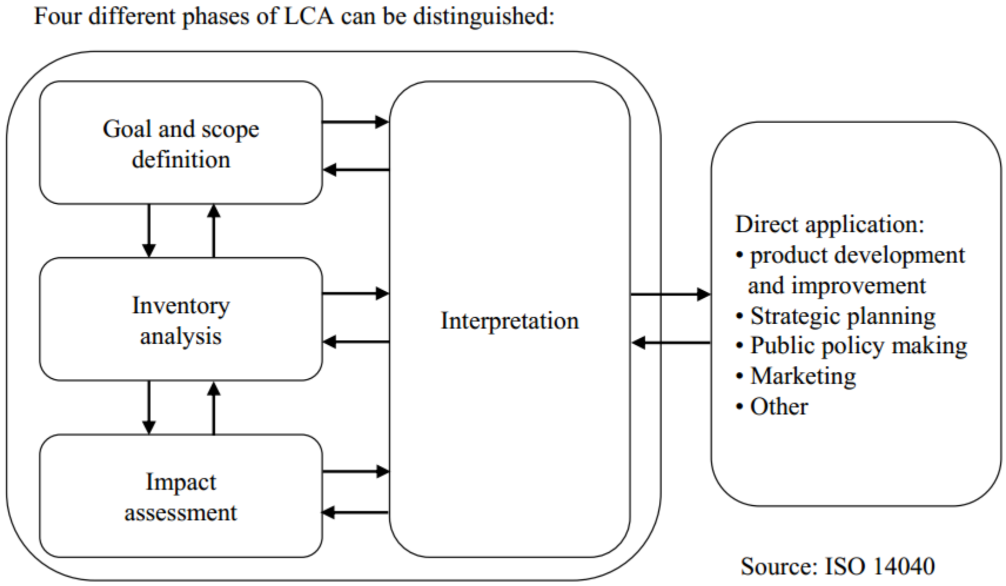


Figure 1.2. ISO required phases for life cycle assessment

1.7.1. Goal and Scope Definition

The "goal and scope" stage in an LCA typically includes several important components: general goal(s), function and functional unit, system boundary, data requirements, assumptions, and limitations. The goal defines the purpose of the LCA and the functional unit defines the quantification of the identified function of the product. For example, in an LCA for wooden floor within a house, the function of a wooden floor requires small pieces of wood materials. It is possible to estimate the average material or energy input and output to produce each piece of wood in, for instance, 1 m^3 of flooring.

1.7.2. System Boundary

A system boundary defines the unit process, or stages, of a processing or production system to be included in the LCA. The system boundary usually depends on the goal and scope definition of an LCA. Depending on the purpose and system boundary, LCA studies can be divided into several categories: cradle-to-gate, gate-to-gate, and cradle-to-grave. For example, Milota et al. (2015) evaluated the environmental impacts for softwood lumber production. The system described in this study starts from logs delivered to the sawmill and ends with dry lumber leaving the sawmill. The study does not consider forestry processes such as planting and harvest, nor does it consider the use and disposal phases of the product, and therefore, it is considered a gate-to-gate LCA. On the other hand, the study conducted by Puettmann and Wilson (2007) established a cradle-to-gate LCA for wood building materials, where the system boundary starts from the forest growth/regeneration stage and ends when the wood products are transported to the building site. This research will develop an LCA that includes the forestry operation, lumber production, transportation, manufacturing, and end-of-life treatments associated with CLT.

Figure 1.3 illustrates the system boundary for assessing the environmental impacts of CLT production in this research. The system starts from forest growth and ends when the materials are treated with different end-of-life options after the building is demolished. Since the environmental performance of one building is not the primary focus of this study, the life cycle stages associated with the construction and usage phase (i.e. energy consumption, maintenance, repairs, etc.) of the building are excluded from the system boundary.

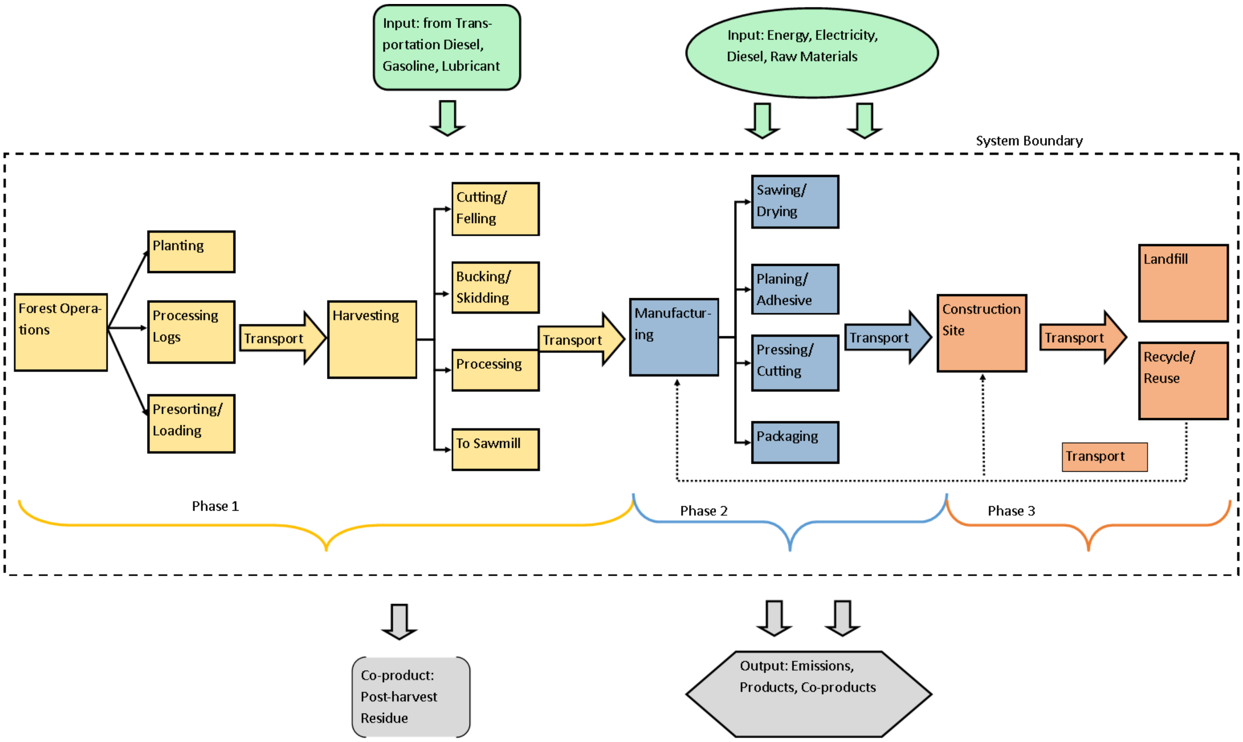


Figure 1.3. System boundary of the life cycle analysis for CLT performed in this research

1.7.3. Data Collection and Inventory Analysis

Inventory analysis is performed by incorporating the collected data and can be analyzed using a range of software tools and models. For LCI analysis, SimaPro and the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) will be used to model the environmental impacts from the processes associated with CLT production. SimaPro is a software tool for modeling production and processing systems from a life-cycle perspective based on the system flow developed by the user. SimaPro integrates life cycle inventory data such as the U.S. Life Cycle Inventory Database ("USLCI" 2012). The Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) is a method developed by the U.S. Environmental Protection Agency (EPA) to estimate the environmental impacts of a specific process system and is integrated in SimaPro. TRACI uses a number of impact indicators at different scales to present the level of impacts from a product's life cycle (Table 2). Although there are many available methods for inventory analysis, TRACI was selected because it is designed specifically for the U.S., which makes it consistent with the area of interest for this research.

In general, an LCA takes into account the energy and material inputs and outputs over a production process and evaluates the impacts based on primary or secondary data. Primary data often involves first-hand data collection through surveys, observations, and experiments specifically designed for the context of the study. An example of primary data may include collecting the amount of electricity or water used to manufacture a product at the production facility. To reduce time and resources, many existing LCA studies use secondary data, meaning the data is either from previous research or from an inventory database specifically designed for LCA. An LCA database contains measurements of material, energy, and environmental flows in and out of the production system for a defined amount of product. Existing LCA databases that are commonly used in North America include the U.S. Life Cycle Inventory Database (USLCI) and Athena. The USLCI was developed by the National Renewable Energy Laboratory (NREL) and contains individual accounting data of energy and material flows associated with many product systems. The Athena Sustainable Materials Institute developed the Athena database and provides data associated with construction materials, including energy use, transportation, construction, maintenance, demolition. The process of collecting and analyzing these data is referred to as life cycle inventory (LCI) analysis. This research also incorporates Ecoinvent, a life cycle inventory data provider in Switzerland (Weidema et al. 2013). Ecoinvent has updated its database to include adjusted inventory data that goes beyond Switzerland and can be applied to countries outside of Europe.

1.7.4. Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) is performed based on the most relevant impact categories associated with the targeted products. The impacts of a system process are calculated based on the characterization factors. The characterization factors are measured based on scientific knowledge and models and are used to quantify the emission contribution of a number of trace substances. The total emission is the summation of emission contribution of each gas calculated using quantity of gas (i) generated from the system or process, multiplied by the characterization factor of that gas (i), which can be expressed as:

$$Impact = \sum Charaterization\ Factor_i \times Emission_i$$

For example, if we are interested in calculating the contribution of methane (CH_4) to the global warming impact category and it is known that the characterization factor for methane is 28 on a 100-year timeframe (Stocker 2014). The global warming impact of methane can be calculated using the function below:

$$GW\ Impact_{CH_4} = 28\ \times Emission_{CH_4}$$

To better understand the expressions used for LCA impacts, Table 1.2 shows some of the key impact categories and the units used for expression.

Table 1.2. Common life cycle impact categories and units

Impact Category	**Impact Scale**	**Unit**
Global Warming	Global	kg CO_2 equivalent
Acidification	Regional/Local	kg SO_2 equivalent
Photochemical Smog	Local	kg O_3 equivalent
Eutrophication	Local	kg N equivalent
Stratospheric Ozone Depletion	Global	kg CFC-11 equivalent

1.8. Area of Study and Site Identification

This research focuses on western Washington and five mid to large size sawmills in this region are used to model the transportation logistics. Two hypothetical CLT mills are modeled in this research: one is located near the City of Forks in Clallam County and the other near Darrington in Skagit County, since these two counties have expressed interest in seeking the opportunities and partners to establish CLT mills as a way to recover from their declining timber production (Watts and Helm 2015). The selection of sawmills is based on data provided by the Washington Department of Natural Resources (DNR). Figure 1.4 shows the distribution of sawmills across Washington's counties. According to the DNR's sawmill survey (DNR 2017), for any lumber-producing counties in western Washington, the lumber supply should be more than enough to supply a large capacity CLT mill. Sawmills modeled in this research are selected from several lumber supplying counties, including Clallam, Grays Harbor, Pacific, Skagit, and Snohomish.

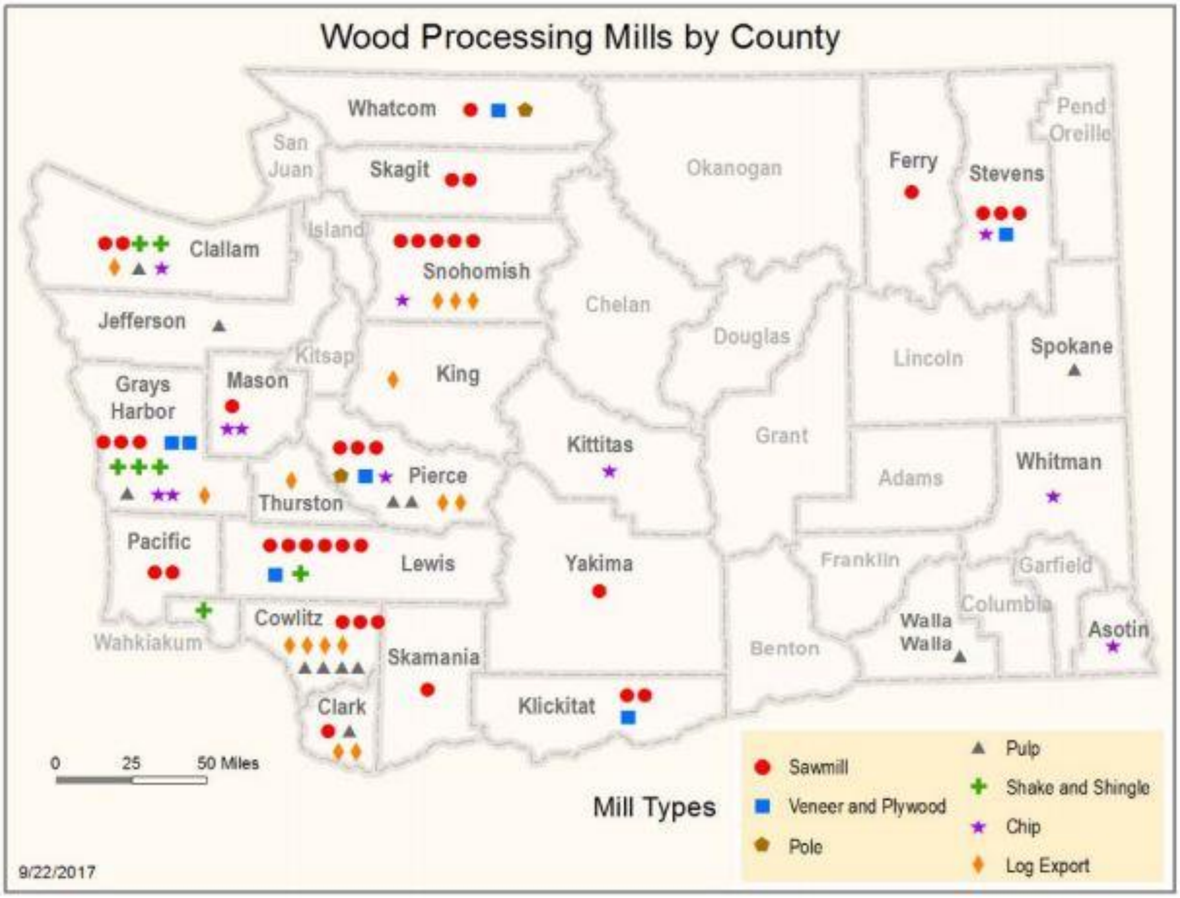


Figure 1.4. Wood processing mill types in Washington's counties (DNR 2017).

As a newly introduced product, not many LCA studies of CLT exist in the PNW. One of the obstacles for conducting research associated with CLT is that it is not yet widely manufactured in the U.S. Although Oregon has established the first certified CLT manufacturing plant in the PNW, there is no formal CLT manufacturing capacity in Washington. Because of this, data associated with in-forest activities and biomass sourcing need to be collected before conducting a life cycle analysis.

1.9. Transportation Analysis

Transportation is one of the primary focuses of this research. The travelling distances between facilities are modeled using a Geographic Information System (GIS), accounting for parameters such as road restrictions, accessibility, and mode of transportation. The environmental impacts of transportation may rely on several factors, including route selection and the mass of materials. Routes are modeled for any transportation involved during the production of CLT and the EoL phase, for example, lumber transportation from the selected sawmills to the CLT mills and the transportation of CLT materials to the landfills. Each route is modeled based on street/highway network data and under preset conditions. Data associated with the GIS routing model (i.e. distance, travel time) is applied to the LCA to quantify the environmental impacts of transportation.

1.10. End-of-Life Analysis

Some of the inventory data for recycling and reprocessing demolished wood materials may be found in previous literature. For example, Lippke and Puettmann (2013) developed end-of-life scenarios for clean demolished building materials (CDM) and used the inventory data of products with similar process stages: recycling CDM for lumber is similar to the process stages of producing lumber, reprocessing CDM for OSB is similar to the process of producing OSB. In the case of CLT, it may be more appropriate to reuse the material due to its higher mass and strength, which make it more durable for uses in other construction after demolition. The Washington’s Department of Ecology (DOE) also provides data associated with waste treatment facilities and the amount of waste generated from construction.

Common EoL treatments for construction materials in Washington includes landfilling, incineration, recycling, and reuse. With consideration for current technology and potential changes in the future, an EoL case scenario is developed for CLT materials. This EoL scenario, developed based on current practice and data, includes landfilling, incineration, and reuse. Methane (CH_4) emission from landfill disposal is calculated based on the condition of landfills, decay level of the wood portion, and additional emissions are modeled based on life cycle inventory data. The emissions from incineration and reuse are also modeled using LCA, and the total impacts of these treatment options represent the total impact of EoL.

1.11. Problem Statement and Rationale

As a type of engineered wood products, CLT has many compelling applications, particularly among the construction industry. However, CLT is relatively new in North America and few studies in the U.S. have focused primarily on CLT (Frangi et al. 2009; Harris 2015; Laguarda Mallo and Espinoza 2015; Pei et al. 2016). Although there is great potential for CLT production in the PNW because of forest abundance and many socioeconomic drivers, the knowledge associated with the environmental impacts of its production, manufacturing, usage, and end of life remains uncertain.

Research studies have suggested that using wood materials in construction projects confers environmental benefits in various aspects compared to alternative materials, implying there could be potential environmental benefits in using CLT. However, due to differences in physical and structural features between CLT and other existing wood products (i.e. lumber, plywood, OSB, I-joist, etc.), the carbon storage and end-of-life aspects may vary significantly compared to previous studies associated with wood products. For example, most of the literature focused on the carbon benefits from substitution effects of wood materials, but the physical features of CLT may allow the material to have longer service life, and the structural design of CLT makes it easier to handle and reuse at the end-of-life stage.

Additionally, CLT may be different from traditional wood products in terms of sourcing, production process, applications, and usage requirements. For instance, small trees are usually not included as a source for long-live wood product, or they are considered as part of post-harvest residuals in some studies (Matsumoto et al. 2017). In the case of CLT, small trees may be used as a source for raw materials and therefore lead to changes in forestry processes such as rotation, thinning, and harvesting strategies. The requirements for CLT used for construction projects may also differ from using alternative products in terms of quantity and energy, leading to uncertainties of whether or at what level CLT is efficient. It is necessary to compare the functionality of CLT components to traditional material components in a construction project to understand the differences and advantages of CLT materials. Changes in forest and usage dynamics may significantly influence the supply chain of wood products, as well as the overall environmental performance of wood construction materials.

Moreover, although there are existing studies that deal with the environmental aspects of wood products and wood-based construction material, few have conducted an environmental assessment that considers regional-specific and case-specific analysis on the end-of-life. Many studies investigating the end-of-life impacts of construction materials are based on system scenarios (Zabalza Bribián et al. 2011), but the end-of-life treatment scenarios lack explicit explanations (Sandin et al. 2014). For example, even though the reuse option often requires more time and energy, it is a more feasible option for CLT components since they are designed as individual prefabricated elements (Robertson et al. 2012). Many uncertainties exist because of the significant variations among construction projects, such as geographical location, logistics, building features, and recycling options, which can lead to variations in material quantities, transportation options, and energy requirements.

To make CLT an environmentally favorable material to use, extensive studies are needed. However, as of today, few have conducted thorough research on CLT production and its impacts in the U.S., from raw material acquisition to end-of-life treatments. CLT is a new product to the U.S. and the lack of research has led to knowledge gaps associated with regional-specific data such as resource availability, material flow, material quantity, impacts to the surrounding environment, and the role of CLT in promoting the use of sustainable construction materials, etc. The lack of knowledge implies an immediate need for more research that focus on CLT in the U.S.

LCA is useful for evaluating the environmental impacts of CLT throughout its supply chain since it includes all relevant stages within the life cycle of CLT, including raw material acquisition, manufacturing, usage, and landfilling/recycling. The life cycle perspectives of wood products are well-documented, but the LCA inventory needs to be updated as more innovative wood products are introduced. One limitation of the current LCA database is the lack of available LCI data for CLT in the U.S. Since CLT originated in Europe and most of the existing LCA studies associated with CLT are based in European countries, the inventory data and LCA results of these studies may not be applicable for the U.S. Variability in factors such as forest management practices, manufacturing processes, and transportation logistics may present significantly different LCA results. Significant uncertainties remain regarding the applicability of existing data to a wide range of wood products, and up-to-date case and regional-specific data are needed to assess the impacts of CLT in greater detail. There is a need for environmental assessment that accounts for broader aspects among construction materials, which means developing an assessment that goes beyond material manufacturing and whole-building LCAs. Conducting a comprehensive LCA of CLT production in the U.S. would not only evaluate the environmental impacts of CLT, but also provide LCI data specifically applicable to the domestic forestry sector and logging industry. It is a critical task to develop comprehensive environmental assessments that are applicable for CLT establishments in the PNW as it is one of the first and primary regions to introduce CLT in the U.S., but there exits many knowledge gaps regarding the feasibility and environmental impacts of CLT production. Therefore, this research will attempt to fill some of the knowledge gaps by answering several important questions associated with the environmental aspects of CLT production and application in Washington.

1.12. Research Goal and Objectives

The overall goal of this research is to use life cycle analysis to develop a regionally-specific environmental assessment to evaluate the impacts of CLT production in western Washington, including: a) investigate the impacts of CLT production under different case scenarios and provide a comparative LCA analysis for these scenarios, and b) evaluate the potential outcomes of different treatment options for CLT materials at the end-of-life phase.

The following objectives, which are designed to reach the research goal described above, are described in their subsequent chapters:

1. Conduct an assessment for CLT production in western Washington using LCA (Chapter 2).

a. Complete a cradle-to-gate LCA using existing sawmills in western Washington.

    i. Identify several sawmills and determine two hypothetical CLT mills to develop a cradle-to-gate LCA.

b. Evaluate the influence of different parameters (i.e. travelling distance and wood species) during CLT production and provide a comparative analysis.

    i. Develop a base case scenario using selected sawmills and common wood species mix, a 50-50 mix of Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*).

    ii. Evaluate and compare different case scenarios by changing transportation logistics and wood species.

2. Investigate the effects of using CLT vs. other materials in construction and assess the carbon footprint associated with CLT as a construction material at the end-of-life stage.

    a. Investigate potential changes in the amount of construction waste by using CLT instead of concrete and steel (Chapter 3).

        i. Determine the amount of waste reduction.

    b. Determine potential impacts of CLT after demolition and impacts of the waste if disposed of in a landfill (Chapter 3).

        i. Calculate emissions from CLT disposal in landfill.

        ii. Calculate potential methane emission from different types of landfills.

    c. Assess the environmental impacts of CLT using LCA (Chapter 4).

        i. Develop a practical case scenario based on current waste treatment data.

ii. Develop an LCA model based on the locations of waste treatment facilities and the amount of CLT that goes to each facility and determine potential impacts of CLT in the future.

1.13. Significance of Outcomes

One important motivation for conducting this research is to accommodate the potential changes in Washington's logging industry for higher efficiency and wood usage driven by various socioeconomic, political and technical factors. This study emphasizes on the life cycle assessment perspectives of CLT and investigates the carbon footprint associated with CLT among the construction industry. The outcomes of this research will establish references that are useful to forest managers, businesses, policy makers, and researchers in better understanding the opportunity and environmental impacts of establishing a CLT industry. Washington has historically been a state with large forest coverage area, but the wood product industry has experienced recession over the past few years due to changes in laws and regulations, forest dynamics, and demands among the logging industry. As the housing market recovers, the wood product industry may experience recovery as well. However, the structure and direction of the wood product industry may change to meet contemporary environmental needs and market demands. It is crucial for Washington's forest sector to seek opportunities to rebuild the timber industry and make it more resilient to future economic and political changes. Introducing a new and innovative wood product such as CLT to the timber industry creates great opportunity for reforms. From an economic perspective, the CLT industry creates local job opportunities and helps the regional timber industry. From an environmental perspective, wood-based products have been considered to confer carbon benefits, and sustainably managed forest for commercial purposes is healthy for the ecosystem.

Chapter 2: The Role of Sawmill Locations and Wood Species Mix on the Environmental Impacts of Cross-Laminated Timber Production in Western Washington

This chapter develops a cradle-to-gate life cycle assessment (LCA) of CLT manufacturing. Different parameters, including sawmill locations, wood species mix, and CLT mill capacity are considered, and different scenarios are compared. Five sawmills in western Washington are selected along with two hypothetical CLT mills located near the cities of Forks and Darrington. The transportation distances are modeled using network analysis in ArcGIS. The system modeled in this chapter also considered the distance for transporting CLT to a hypothetical construction site in Seattle.

2.1. Introduction

The supply chain for wood products is composed of a network of forest activities, harvests, processing, and distribution, and each stage within the supply chain can contribute to the total environmental impact (Ramage et al. 2017). Due to the idiosyncratic characteristics of CLT, the impacts resulting from the supply chain may be different from those of other wood products. For example, larger CLT panels may have a length of up to 18 meters and a width of up to 3 meters, which may require special arrangements such as pilot vehicles during the transportation of CLT panels in countries with strict commercial truck dimension/load standards, such as Canada (Ontario Ministry of Transportation 2018; WASHTO 2009). Nonetheless, the truck weight and dimension standards are less restrictive in the U.S. compared to these countries, meaning that a pilot vehicle may not be necessary for regular CLT transportation in the U.S (U.S. Department of Transportation 2004).

Transportation is an important factor associated with forestry operations and wood products according to economic and environmental variability studies (Bergman et al. 2014; Chen et al. 2017; Domke et al. 2012; Michelsen et al. 2008; Zamora-Cristales et al. 2014). Transportation can have various levels of impact depending on the geographical features of the harvest locations and the operational factors. To limit the negative impacts associated with CLT production, it is important to understand the factors that may contribute to environmental burden. Since CLT is a relatively new product to the U.S., research associated with its environmental impacts is very limited. Many studies have emphasized the usage stage of wood buildings and their impacts on the carbon balance (Santi et al. 2016; Corradini et al. 2018; Liu et al. 2016; Takano et al. 2015; Haibo Guo et al. 2017), whereas the association between material source and site-specific CLT panel transportation is not well understood, especially in the U.S. Transportation is an important part in evaluating the embodied carbon of wood buildings and obtaining the materials from a reasonably close source is a premise for carbon storage benefits to take place (Chen 2012; Lehmann 2012; Mallo and Espinoza 2014).

Moreover, Washington has rich forest resources and a well-developed timber industry. Based on the historical data of lumber production, lumber produced in Washington's sawmills is more than enough to supply a normal scale CLT mill. However, the location of these sawmills can directly affect factors such as travel distance and wood species used for production.

CLT has gained an increasing level of recognition in the U.S. over the years and the state of Washington has expressed interest in developing CLT manufacturing in the state. However, few studies have conducted environmental assessment to investigate possible outcomes of establishing CLT manufacturing in Washington and specific measures are required to understand the impacts that may be associated with CLT. This study develops a regional-specific cradle-to-gate life cycle assessment (LCA) for CLT production using data and technology applicable in Western Washington to evaluate the potential environmental impacts of CLT production, focusing on various transportation logistics and different species mixes to provide a comparative analysis for CLT production.

2.2. Study Need and Objectives

CLT has been gaining recognition in the U.S. over the years and the state of Washington has expressed interest in developing CLT manufacturing in the state. Recently, a study estimated the potential use of CLT in various applications for mid-to-high rise buildings in the Pacific Northwest (Ganguly et al. 2017). This study projected that, by 2035, the region can experience an annual demand of 6.6 million cubic feet (or 187,000 cubic meters) of CLT panels, just for mid-to-high rise building constructions. Another project funded by a USFS wood innovations grant undertook a comprehensive supply chain study of CLT production in the Pacific Northwest (PNW), with detailed assessment of material sourcing and various economic assessments. This study provides the much needed environmental perspective of CLT production in the region, by utilizing the techno-economic analysis developed by Brandt et al. (2018). Specifically, the study described in this chapter performed a region-specific cradle-to-gate life cycle assessment (LCA) for CLT production, using data and technology applicable in western Washington to evaluate the potential environmental impacts of CLT production. In addition, this chapter focused on various location specific material transportation logistics and different species mixes to provide a nuanced understanding of CLT production in western Washington. The objectives of this chapter are: a) to assess the environmental impacts of producing CLT panels in western Washington, and b) to compare environmental impacts based on different logistics and wood species mix. Hence, this study developed a cradle-to-gate LCA based on existing literature and primary data. Several scenarios with different transportation distances and wood mixes were considered. The study compared the changes in environmental impacts when different parameters were used.

2.3. Material and Methods

This section describes the tools and data used for modeling the environmental impacts. This study uses a Life Cycle Assessment (LCA) approach and based on the ISO 14040 and ISO 14044 standards outlined by the International Organization for Standardization (ISO 2006a; ISO 2006b). The environmental impacts of a production or service system are evaluated based on the inputs and outputs of material and energy occurred at each life cycle stage for a defined functional unit of product. The functional unit is defined as the quantification of the identified function of the product. In this study, a functional unit of 1 m^3 of CLT was used.

The material estimates used in this study were drawn from the Techno-Economic Analysis (TEA) for manufacturing cross-laminated lumber (Brandt et al. 2018), which was undertaken with reference to manufacturing CLT in the PNW. A CLT mill with a manufacturing capacity of 52,283 m^3 per year (small scale mill) was considered in this study. All the material and energy estimates used in this study were drawn from the aforementioned TEA, including the resin type, the resin volume estimates, and the energy estimates at various stages of the manufacturing process. SimaPro 8 was used to perform the LCA analysis. SimaPro incorporates different LCA databases and impact assessment methods. While most input data were adapted from the TEA, data for processes such as electricity generation, lumber production, and fuel consumption were obtained from the U.S. Life Cycle Inventory database (USLCI). Inventory data the production of resins used in the CLT came from a combination of LCI databases and existing literature. The amount of materials required for PUR resin production was obtained from Messmer (2015), and the inventory data of the production of these required materials were obtained from the USLCI and the Ecoinvent databases.

The impacts are quantified using multiple life cycle impact assessment categories, known as LCIA categories. Each impact category is modeled using scientific-based conversion factors known as characterization factors (Curran 2006; Solomon 2007; Stocker 2014). For example, global warming potential (GWP) is expressed in terms of “CO_2 equivalent”, or “CO_2 eq.” since the GWP is modeled using CO_2 as the reference gas. The impacts of a process or system may be modeled at different timeframes with the corresponding characterization factors. The most common timeframe used in current LCAs is 100 years, but 20 and 500-year timeframes may be used as well. LCA is a useful tool for assessing the impacts of a product or system and it has been widely applied in recent years in the wood product sector.

2.3.1. System Boundary

The system boundary, shown in Figure 2.1, started at the forest and ended at the construction site, where the CLT material was delivered. Accordingly, the products and processes factored-in within this LCA analysis included forestry activities, material extraction, manufacturing, transportation, and CLT panels delivered to the building construction site. There were three main stages within the system: forestry activities and resource extraction, lumber production, and CLT production. Impacts associated with building construction, building usage, demolition, and end-of-life were not included in this study. It may also be noted that processes such as the manufacturing of capital equipment, facility maintenance, and labor costs were beyond the scope of this study.

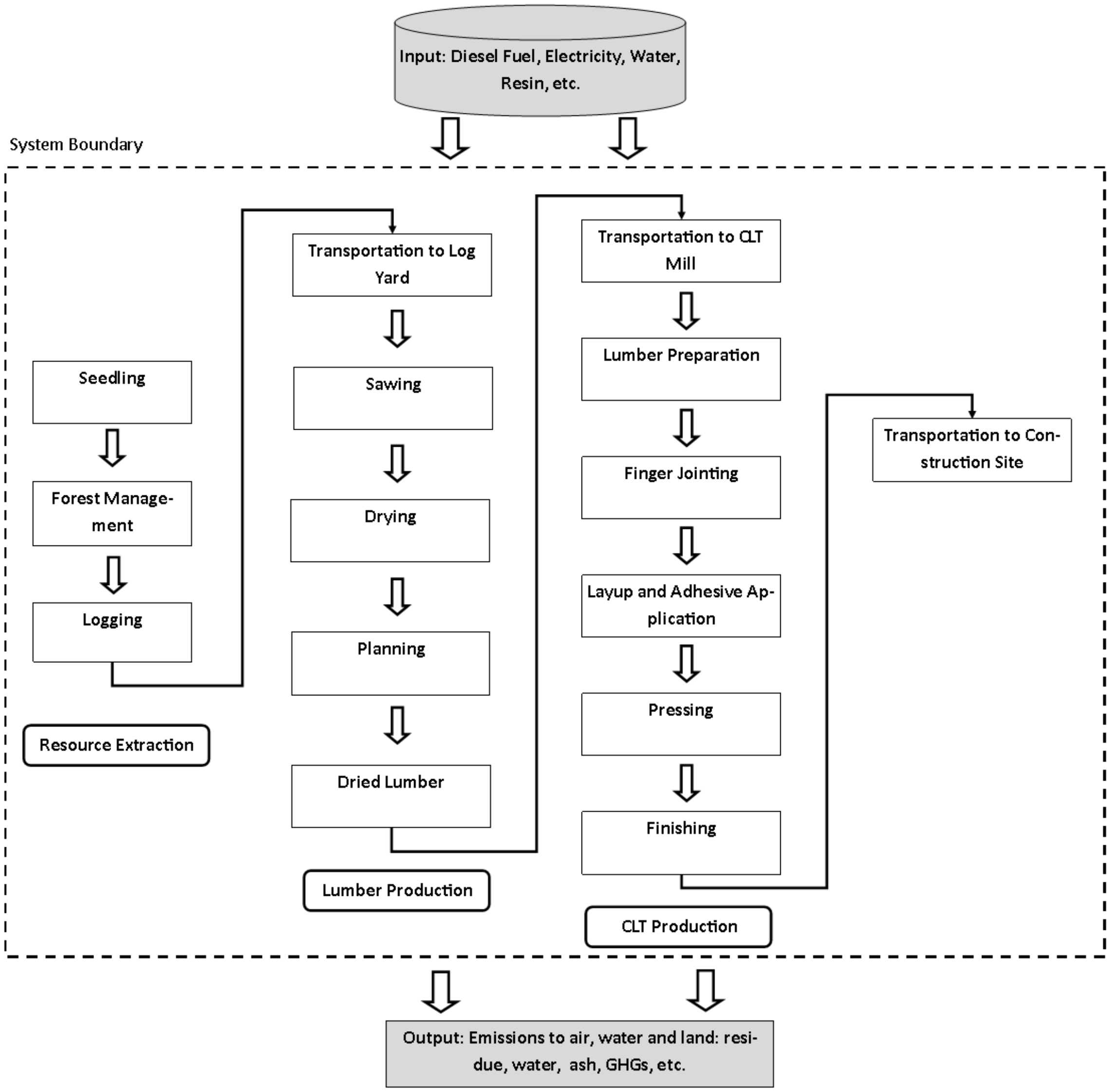


Figure 2.1. System boundary describing the stages involved in the cradle-to-gate LCA.

2.3.2. Assumptions

Several assumptions are made during input calculation and data analysis in terms of material composition, moisture contents, and wood characteristics:

1. For the baseline scenario for CLT production, 50% Douglas-fir and 50% western hemlock, was considered. The bone-dry lumber density for the aforementioned species mix was assumed to be 466 kg/m^3, in the baseline scenario (Milota 2015).
2. Other wood species mixes were considered in the sensitivity analysis: the bone-dry density of lumber constituted of Sitka spruce was assumed to be 360 kg/m^3, and that of lumber constituted entirely of Douglas-fir was assumed to be 480 kg/m^3.
3. Based on the TEA data, the amount of lumber needed to produce 1 m^3 of CLT was assumed to be approximately 1.21 m^3.
4. The moisture content of CLT panels was assumed to be 12% ± 3%.
5. The construction site where the CLT panels were delivered was assumed to be located in the city of Seattle, WA.

2.3.3. Impact Assessment

The life cycle impact assessment included several indicators that describe the level of impacts generated by a process or system. The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) was used to model the environmental impact. TRACI is a method developed by the U.S. Environmental Protection Agency (EPA) to estimate the impacts of a specific process system and includes impact indicators at the global, regional, and local levels. As shown in Table 2.1, the impacts considered in this study included global warming potential (GWP) (CO_2 equivalent), acidification potential (SO_2 equivalent), photochemical smog potential (O_3 equivalent), eutrophication (N equivalent) and stratospheric ozone depletion potential (CFC-11 equivalent). The five impact categories shown in Table 2.1

are consistent with the categories required for environmental declaration of wood products in North America (FPInnovations 2015; ISO 2017).

Table 2.1. Major impact categories used to evaluate the level of impacts from the system.

Impact Category	Impact Scale	Unit
Global Warming	Global	kg CO_2 equivalent
Acidification	Regional/Local	kg SO_2 equivalent
Photochemical Smog	Local	kg O_3 equivalent
Eutrophication	Local	kg N equivalent
Stratospheric Ozone Depletion	Global	kg CFC-11 equivalent

The impact on global warming of a process or system may be modeled at different timeframes. In accordance with the practice within the North American wood products LCA, in this study, the impact on global warming was calculated using a 100-year timeframe.

2.3.4. Lumber Inputs

The main material for CLT manufacturing is lumber. Lumber may be produced from a wide variety of tree species and have different densities depending on the raw materials mix. In the western Washington raw materials for lumber may include a mix of common tree species such as Douglas-fir, western hemlock, spruce, and other conifers. The minimum specific gravity (SG) requirement of lumber for CLT manufacturing is 0.35, or a bone-dry density of 350 kg/m^3 (APA-The Engineered Wood Association 2012; Karacabeyli and Douglas 2013), but common tree species such as Douglas-fir and western hemlock have SG that range from 0.45 to 0.48. If a 50-50 mix of Douglas-fir and western hemlock is used, the bone-dry mass of the wood portion of CLT is approximately 466 kg/m^3. The lumber input requirement for CLT manufacturing is adopted from multiple studies (Brandt et al. 2018; Athena Sustainable Materials Institute 2013; Puettmann et al. 2018) and 1.21 m^3 of lumber is assumed for every m^3 of CLT. The LCA for softwood lumber by Milota (2015) is used to assess the impacts from lumber production.

2.3.5. Transportation

To compare the environmental impacts associated with transportation logistics, five sawmills in western Washington were selected based on various factors including size, location, capacity, etc. The selected sawmills include Sierra Pacific sawmill operations located in Aberdeen and Burlington, Hampton lumber mill in Darrington, Interfor sawmill in Port Angeles, and Weyerhaeuser located in Raymond. The sawmills were all mid to large scale sawmills in terms of production capacity, which make them plausible suppliers for potential CLT mills in Washington. Two potential CLT mills were hypothetically located near the cities of Forks and Darrington. Both locations have long traditions of lumber production and are looking to develop CLT manufacturing facilities in the area. Both areas are home to timberlands and various tree species, including the major raw material for softwood lumber such as Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and Sitka spruce (*Picea sitchensis*). These locations are also viable sites for supplying CLT to major cities across the state. A construction site is assumed to be located in Seattle, WA. The locations and routes between the facilities are shown in Figure 2.2.

Since the transportation conditions of materials between forests, sawmills, CLT mills, and construction sites may vary widely depending on geographical factors, the selected sawmill sites are scattered around different regions across western Washington to produce a better representation of logistics conditions. Highways are usually located within accessible range for all of the selected sawmills. The location of the sawmills may also affect the wood species used for lumber production.

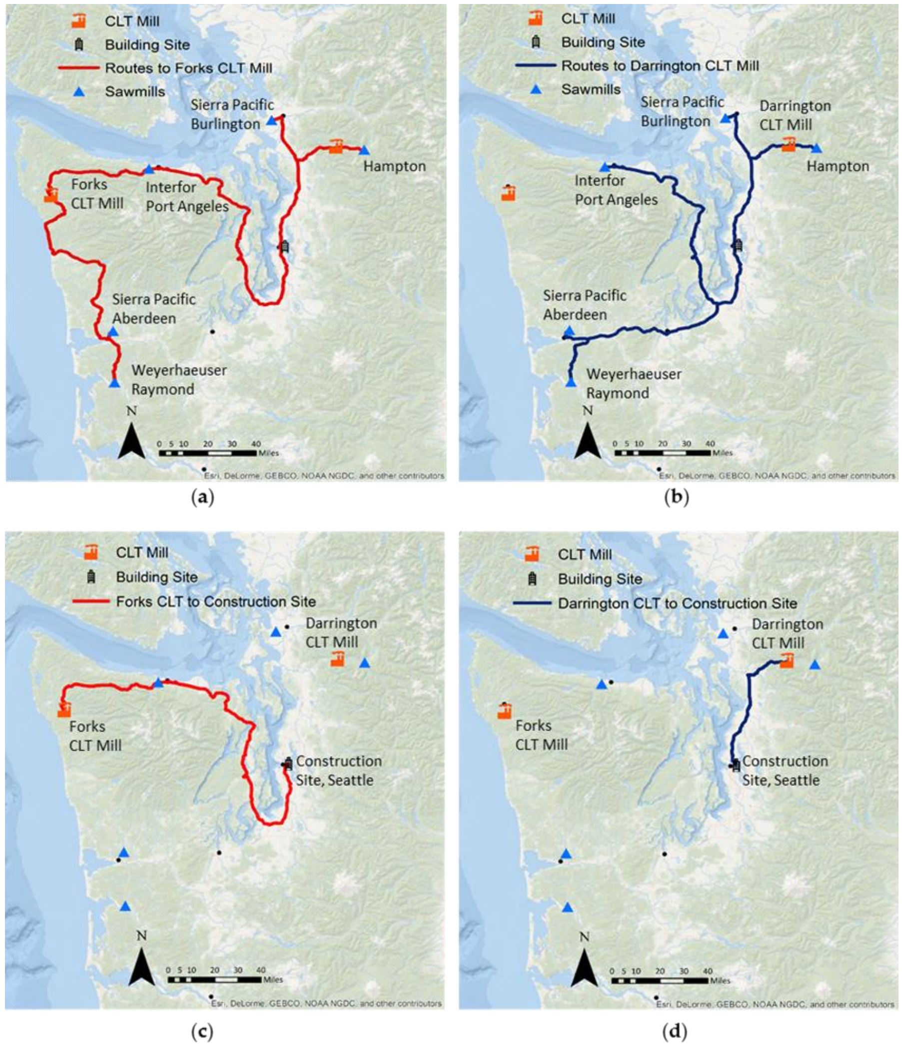


Figure 2.2. Maps of Western Washington, indicating the locations and travelling routes of the selected sawmills, hypothetical CLT mills, and construction site: (a) Transportation routes from sawmills to CLT mill in Forks; (b) Transportation routes from sawmills to CLT mill in Darrington,; (c) and (d) Transportation routes from the two hypothetical CLT mills to a building site in Seattle.

One key aspect of this study is accounting for the impacts associated with material transportation and considering the effects of transportation distances. Table 2.2 shows the distances between the selected sawmills, hypothetical CLT mills, and the final construction site. Combination truck was used for transporting the lumber to the CLT mills for CLT production. ArcGIS is used to model the transportation distances between the sawmills and the CLT mills. Since larger commercial trucks are needed to transport the lumber used for CLT manufacturing, certain road restrictions are taken into account. For instance, water transportation such as ferries was strictly avoided and roads that do not allow truck access were also avoided during GIS modeling. The finished CLT panels were transported to the construction site from the CLT mills.

Table 2.2. Transportation distances from selected sawmills to potential CLT mills, and from CLT mills to the construction site.

Transportation of Lumber and CLT	**Mode**	**Distance (km)**
To Forks CLT Mill	Truck	
Hampton Sawmill		440
Interfor Sawmill (Port Angeles)		91
Weyerhaeuser (Raymond)		206
Sierra Pacific Sawmill (Aberdeen)		174
Sierra Pacific Sawmill (Burlington)		431
To Darrington CLT Mill	Truck	
Hampton Sawmill		21
Interfor Sawmill (Port Angeles)		330
Weyerhaeuser (Raymond)		302
Sierra Pacific Sawmill (Aberdeen)		284
Sierra Pacific Sawmill (Burlington)		76
To Construction Site	Truck	
Forks CLT Mill		322
Darrington CLT Mill		104

2.3.6. Wood Species Mix

Finally, this study considered differences associated with regionally specific wood species mixes used for CLT production. CLT usually consists of 3, 5, or 7 layers of lumber pressed together in alternate directions. Layers in the same direction as the surface layer (the first layer) are referred to as the parallel layers. Generally, parallel layers use better structural graded lumber, while the perpendicular layers can use lumbers of lower structural grade. The baseline scenario used lumber produced with a 50–50 mix of Douglas-fir and western hemlock, adapted from Milota (2015). Douglas-fir lumber is known for its superior dimensional stability and is likely to have greater aesthetic appeal as compared to western hemlock. Using structural/visual graded lumber for all the layers of CLT is neither necessary nor efficient to attain specific visual grades (V grades) or elasticity grades (E grades) of the CLT panels. Accordingly, different species (in this case, Douglas-fir, Sitka-Spruce and western hemlock) and various structural and visual grades were considered in this study. Different wood species mixes and their overall impacts in the process are discussed in detail in the sensitivity analysis section.

2.3.7. CLT Manufacturing Inputs

CLT manufacturing involves several key phases, including lumber preparation, finger jointing, layup and adhesive application, pressing, and panel finishing. Multiple steps are involved in each key process during manufacturing and require inputs such as fuel and electricity. For example, lumber preparation involves lumber selection, drying, grouping, and cutting. and requires different equipment to kiln dry and cut the lumber. Depending on the capacity of the CLT mills, the manufacturing processes may vary slightly (Karacabeyli and Douglas 2013).

In this study, a CLT mill capacity of 52,283 m^3 per year was considered. Table 2.3 shows the materials included in 1 m^3 of CLT. The main components in a CLT panel include resin (adhesives) and wood. Approximately 6.44 kg of resin is required for every m^3 of CLT. Inputs for CLT manufacturing are calculated based on Brandt et al. (2018). Mass allocation was applied in this study, assuming 17% of the lumber input becomes hog fuel at the end. The amount of co-products from CLT manufacturing were adapted from Puettmann et al. (2018) and values were adjusted based on the amount of production relative to this study. This study assumes that the CLT produced in the mills consists of 50% 3-layer CLT and 50% 5-layer CLT. The amount of primary product and co-products are shown in Table 2.3.

Table 2.3. Primary products from 1 m^3 of CLT, including wood and resin portions.

	Unit	Amount
Primary Product		
CLT	m^3	1
	odkg	472.44
Wood Portion	odkg	466
Resin	kg	6.44
Co-Products (Used for Hog Fuel)		
Shavings	odkg	19.45
Finger Joint Waste	odkg	5.25
CNC Waste and End Cuts	odkg	72.06

2.3.8. Energy Inputs

Electricity and fuel are required for CLT manufacturing. The amount of inputs depends on factors such as technology, efficiency, and available equipment of each mill. Table 2.4 shows the energy input to each process involved in CLT manufacturing. Resin inputs are required in both the finger jointing and the face bonding processes, while natural gas is required for lumber drying. Electricity is the main energy input for operating the equipment used in the processes. Capital costs and the production impacts of the equipment are not included in this study.

Table 2.4. Amount of energy inputs during on-site manufacturing of 1 m^3 of CLT.

	Unit	**Amount**
Primary Product		
CLT	m^3	1
Inputs		
Lumber Preparation	kWh	44
	m^3 – Natural Gas	2.63
Finger Jointing	kWh	32
	kg – Resin	1.61
Lay Up and Adhesive Application	kWh	3
	kg – Resin	4.83
Pressing	kWh	18
Panel Finishing	kWh	31.75

2.4. Results

The results of impact analysis from the transportation phase and the manufacturing phase of CLT are presented in this section.

2.4.1. Impacts of Lumber Transportation

The impacts of transportation strongly depend on the distance and road conditions. As shown in Figure 2.3, the GWP resulting from transporting 1.21 m^3 of lumber from a sawmill to a CLT mill in Forks can range from 6 to 29.16 kg CO_2 eq., while the GWP for transporting lumbers to a CLT mill in Darrington can result in 1.36–21.88 kg CO_2 eq. Similarly, other impact categories show an increasing trend along with increases in travelling distance (Tables 5 and 6). For example, the smog potential resulting from the transportation of lumbers from the selected sawmills to Forks' CLT mill ranges from 1.15 to 5.57 kg O_3 eq., and the smog potential from the transportation of lumbers from the selected sawmills to Darrington's CLT mill ranges from 0.26 to 4.18 kg O_3 eq. Assuming the impacts from lumber production stay constant, there could be up to a 95% reduction in GWP associated with lumber transportation when a closely located sawmill is used to supply 100% of the lumber for CLT manufacturing.

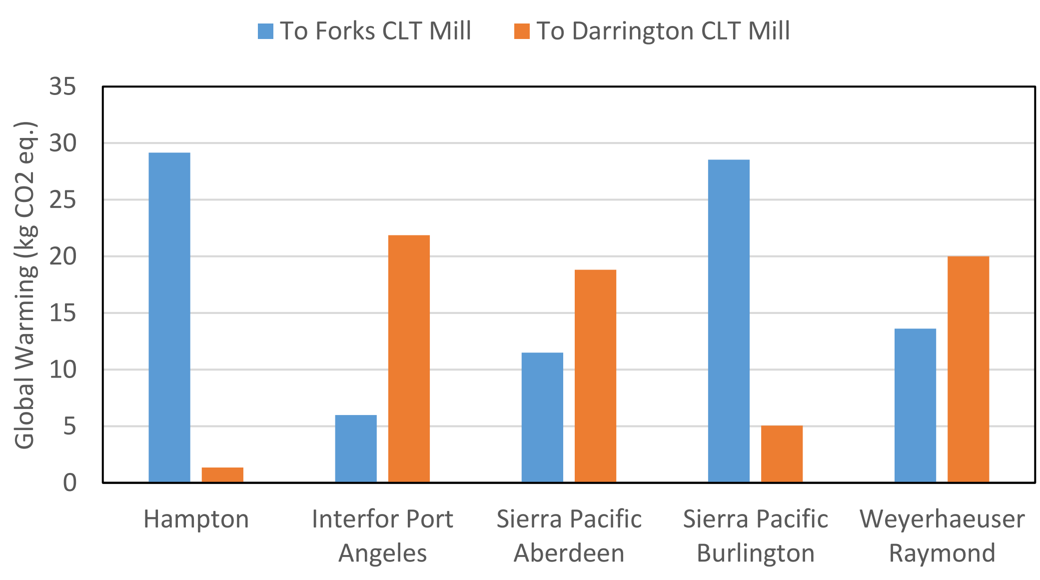


Figure 2.3. GWP resulting from transporting lumber from the selected sawmills to the potential CLT mills.

Table 2.5. Impacts of transporting lumber (lamstock for 1 m^3 of CLT) from selected sawmills to CLT mill in Forks, WA.

Impact Category	**Sawmills to Forks CLT Mill**				
	Hampton	Interfor Port Angeles	Sierra Pacific Aberdeen	Sierra Pacific Burlington	Weyerhaeuser Raymond
Global Warming (kg CO_2 eq.)	29.16	6.0	11.5	28.55	13.62
Acidification (kg SO_2 eq.)	0.21	0.042	0.081	0.2	0.096
Eutrophication (kg N eq.)	0.011	0.0024	0.0045	0.011	0.0053
Smog Potential (kg O_3 eq.)	5.57	1.15	2.19	5.45	2.6
Ozone Depletion (kg CFC-11 eq.)	1.2E-09	2.47E-10	4.73E-10	1.18E-09	5.6E-10

Table 2.6. Impacts of transporting lumber (lamstock for 1 m^3 of CLT) from selected sawmills to CLT mill in Darrington, WA.

Impact Category	**Sawmills to Darrington CLT Mill**				
	Hampton	Interfor Port Angeles	Sierra Pacific Aberdeen	Sierra Pacific Burlington	Weyerhaeuser Raymond
Global Warming ((kg CO_2 eq.)	1.36	21.88	18.82	5.05	20
Acidification (kg SO_2 eq.)	0.0096	0.15	0.13	0.036	0.14
Eutrophication (kg N eq.)	0.00053	0.0086	0.0074	0.002	0.0078
Smog Potential (kg O_3 eq.)	0.26	4.18	3.59	0.96	3.82
Ozone Depletion (kg CFC-11 eq.)	5.6E-11	9.0E-10	7.75E-10	2.08E-10	8.23E-10

2.4.2. Impacts of CLT Manufacturing

As described in previous sections, the manufacturing of CLT requires multiple processes and each of these contributes to the total impacts. As shown in Table 2.7, the total GWP for on-site CLT manufacturing is 96.71 kg CO_2 eq. per unit of CLT. The resin contributes 29.38 CO_2

eq. per unit of CLT, which equates to 30% of the CLT production impacts. After adding the impact from lumber production, the total GWP becomes 155.65 kg CO_2 eq. The results shown in Table 2.7 were calculated using mass allocation. The impact of on-site CLT manufacturing is directly associated with the input from industrial equipment and raw material, as well as the amount of waste generated. Among the steps involved in CLT manufacturing, panel finishing requires the most energy, followed by pressing, as these steps consume the most electricity input. Panel layup and adhesive application also contribute significantly to the impact of on-site CLT manufacturing because of the significant amount of resin required in this step. Lumber production contributes 58.94 kg CO_2 eq. per unit of CLT. Of this, 85% comes from producing lumber, with 15% assigned to forestry operations. Treatment of biogenic carbon is consistent with the IPCC inventory reporting framework. As carbon emissions from biomass combustion are accounted for under the Land Use, Land-Use Change and Forestry (LULUCF) sector, they were not included in energy emissions reporting for the product LCA (Intergovernmental Panel on Climate Change [IPCC] 2006).

Table 2.7. Impacts of lumber production and on-site manufacturing of 1 m^3 of CLT in CLT mill.

Impact Category	Unit	Lumber Production	On-Site CLT Manufacturing	Total (Without Transportation)
Global Warming	kg CO_2 eq.	58.94	96.71	155.65
Acidification	kg SO_2 eq.	0.63	0.81	1.44
Eutrophication	kg N eq.	0.02	0.09	0.11
Smog Potential	kg O_3 eq.	11.19	5.98	17.17
Ozone Depletion	kg CFC-11 eq.	6.18E-09	4.12E-06	4.13E-06

In addition to the on-site manufacturing, the transportation of CLT from the CLT mills to the construction site needs to be considered as it can vary by facility location as well. As shown in Table 2.8, the impact of transporting CLT from the Darrington CLT mill is lower than that of the Forks CLT mill. This is because the construction site is assumed to be in Seattle, which is geographically closer to Darrington than to Forks.

Table 2.8. Impacts of transporting CLT from CLT mills to the construction site (unit: 1 m3 of CLT).

Impact Category	Unit	From Forks CLT Mill	From Darrington CLT Mill
Global Warming	kg CO2 eq.	17.9	5.76
Acidification	kg SO2 eq.	0.13	0.041
Eutrophication	kg N eq.	0.007	0.0023
Smog Potential	kg O3 eq.	3.42	1.1
Ozone Depletion	kg CFC-11 eq.	7.37E-10	2.37E-10

2.4.3. Total Impacts

The overall environmental impacts from CLT manufacturing include impacts from forestry operations, lumber production, resin production, transportations, and on-site manufacturing. The location of production sites plays an important role in the total impacts. The addition of adhesives is also an important factor to consider. Although both lumber production and CLT manufacturing contribute significantly to the total impacts of CLT, changing the manufacturing process of lumber and CLT in an attempt to reduce environmental impacts is technically challenging and may require significant capital investment. Conversely, changing the sourcing of lamstock is a practical solution to reduce the overall environmental impacts of CLT without negatively affecting its economics. For this reason, this study focused on logistics and analyzed in detail the impact of transportation.

The total impacts for all impact categories are provided in Tables 2.5–2.8. Considering GWP, keeping all other processes constant, different contributions from lumber transportation are shown in Figures 2.4 and 2.5. The highest GWP impact is from transporting lumber from the Hampton sawmill to a CLT mill in Forks, reaching over 202 kg CO_2 eq., when including impacts of lumber production, transportation, and on-site manufacturing. CLT manufacturing accounts for the highest proportion of the total impacts. In the case of the CLT mill in Forks, the total impact can be reduced by as much as 11.4% if a close-by sawmill is selected. For the CLT mill in Darrington, a reduction of as much as 11.1% can be achieved. All other impact categories, namely acidification, eutrophication, smog and ozone depletion, show similar trends, and the results are provided in Tables 2.5–2.8.

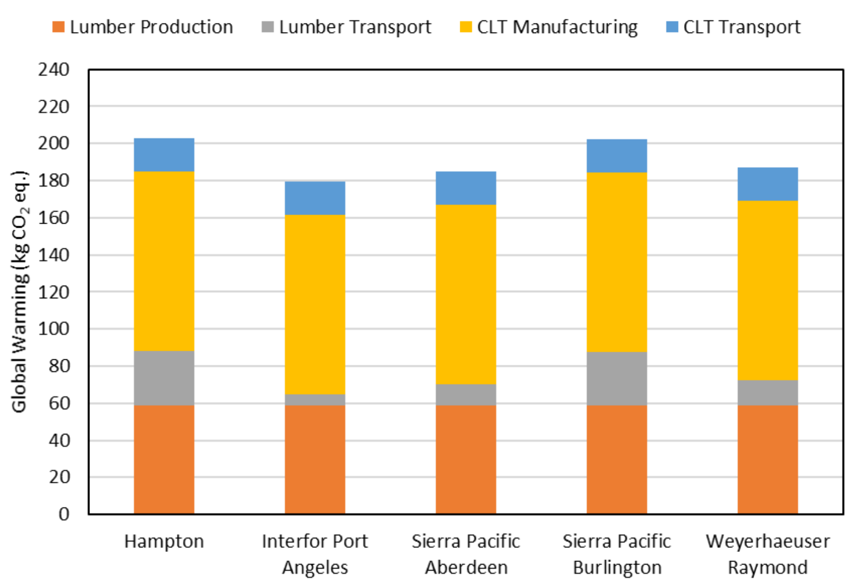


Figure 2.4. Total impacts of 1 m^3 of CLT production in Forks, WA, from the forest site to the gate of the construction site.

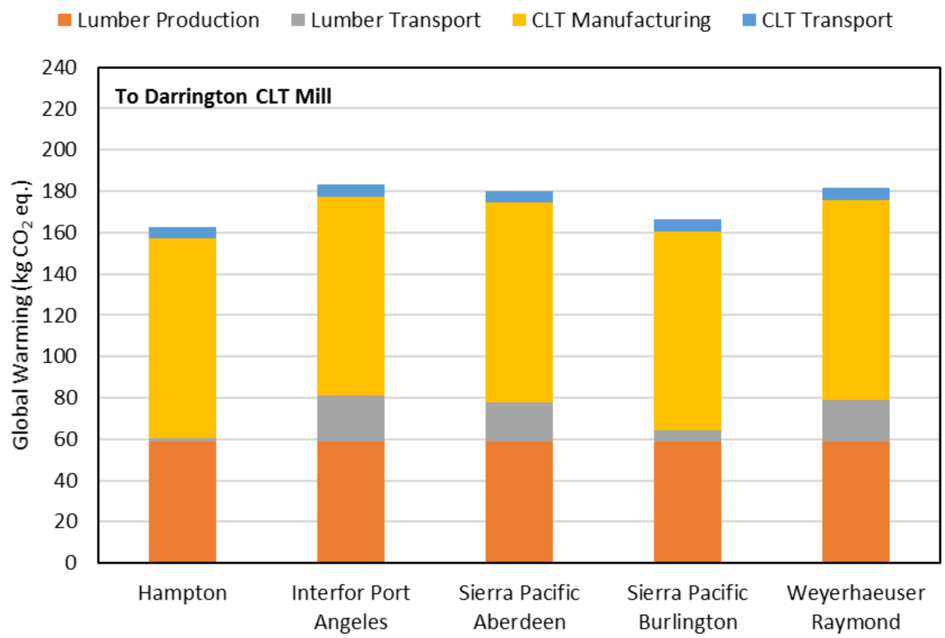


Figure 2.5. Total impacts of 1 m^3 of CLT production in Darrington, WA, from the forest site to the gate of the construction site.

2.4.4. Sensitivity Analysis

In addition to the transportation distance, many other factors may influence the total impacts of CLT production. One key factor is the relative density of materials being transported. The baseline scenario of this study assumed that the raw material for lumber consists of Douglas-fir and western hemlock. However, there are many possible wood mixes for producing lumber and CLT, some of which are lighter materials and some are heavier depending on the SG of the wood species. According to the American National Standard for CLT, there are several different grading standards for CLT: E1, E2, E3, E4, V1, V2, and V3. For example, V1 grade CLT uses Douglas-fir–Larch lumbers on all layers, which is heavier due to higher SG of Douglas-fir (0.48) and western Larch (0.52), while CLT using spruce–pine–fir is significantly lighter (SGs of 0.35–0.4) (Miles and Smith 2009).

A sensitivity analysis was performed to determine the changes in total impacts when different wood mixes were used. This section tests the difference of impacts when using Douglas-fir only (heavier) and using Sitka spruce only (lighter), both very common wood species in the PNW, for CLT production. Sitka spruce is a common species in western Washington and meets the minimum requirement for structural lumber, making it a viable material for CLT. The mass of the lumber required for CLT production was adjusted according to the SG of the new wood species mix. While the transportation distances between facilities remained constant, the input data for the LCA model changed because of the different SG, which, in turn, changed the environmental impacts.

Figures 2.6 and 2.7 show the differences in GWP from transporting lumber made of a Douglas-fir and western hemlock mix (baseline case), Douglas-fir only, and Sitka spruce only. Because Sitka spruce is noticeably lighter than Douglas-fir and western hemlock, there is a clear declining trend in GWP under all transportation cases. For instance, the impact for transporting spruce-only lumber from Hampton sawmill to Forks' CLT mill shows a 29% decrease compared to the baseline case. On the other hand, the impact for using lumber made of Douglas-fir only shows a slight increase compared to the baseline case, but the difference is relatively small. For example, there is a 3% increase in GWP when transporting lumbers made of Douglas-fir only. This is because the SG of Douglas-fir is only slightly higher than that of the Douglas-fir and western hemlock mix. The same decreasing trends are observed for other impact categories: for instance, there is a 3% increase in acidification potential when transporting Douglas-fir-only lumbers compared to the baseline scenario, same as the GWP.

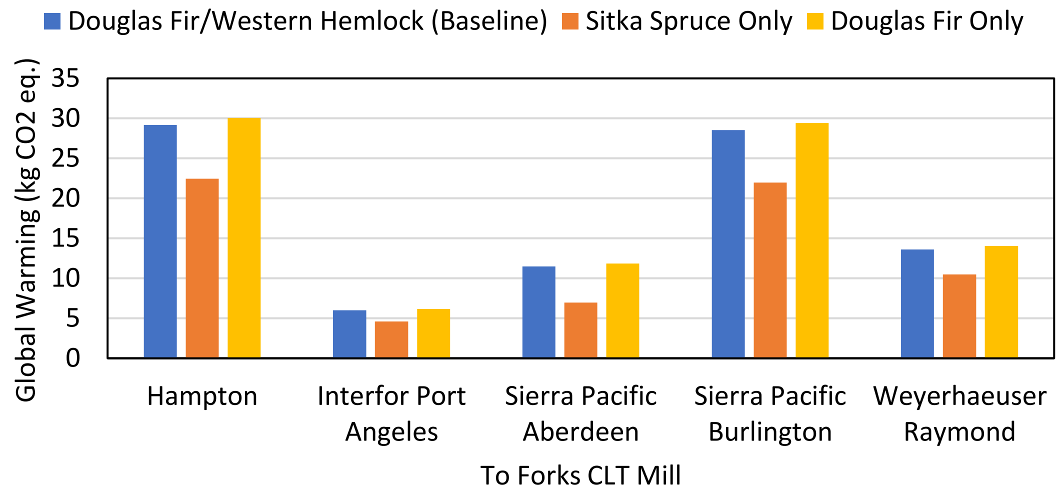


Figure 2.6. GWP of transporting lumber of different wood species from sawmills to CLT mill in Forks, WA. DF represents Douglas-fir, WH represents western hemlock, and SS represents Sitka spruce. The baseline scenario is a 50-50 mix of Douglas-fir and western hemlock (unit: 1.21 m^3 of lumber).

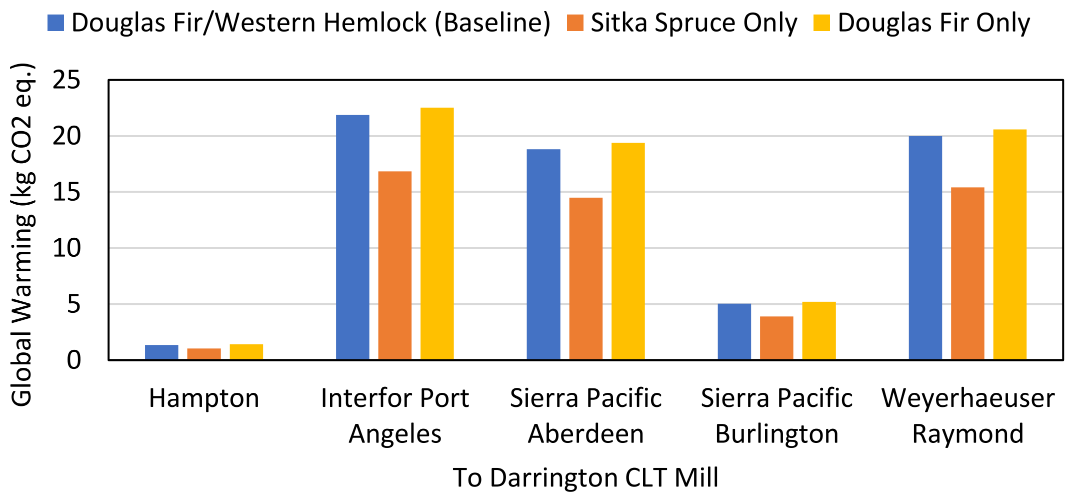


Figure 2.7. GWP of transporting lumber of different wood species from sawmills to CLT mill in Darrington, WA. DF represents Douglas-fir, WH represents western hemlock, and SS represents Sitka spruce. The baseline scenario is a 50-50 mix of Douglas-fir and western hemlock (unit 1.21 m^3 of lumber).

Changes in the type of wood species used can directly influence the choice of the lumber supplier. In this case, although Sitka spruce is a common wood species in western Washington, not all sawmills produce spruce-only lumbers. Sitka spruce is mainly distributed along the coastal areas of PNW and the Puget Sound region. Out of the five selected sawmills, Hampton and Interfor indicate that they supply spruce-pine fir (SPF) lumbers. On the other hand, most of the sawmills in western Washington produce lumbers using Douglas-fir since it is distributed in all forests across the state, which makes Douglas-fir a viable species in all five sawmills. The changes in total GWP as a result of different wood species use are shown in Table 2.9. By using lighter materials for lumber, the reduction in total GWP can compensate for the impacts of transportation. This is particularly important for sawmills located further away from the CLT mills. Hampton sawmill is located the furthest away from Forks' CLT mill, resulting in a total GWP of 185.69 kg CO2 eq. for 1 m3 of CLT under the baseline scenario, where a mix of Douglas-fir and western hemlock was used. If Sitka spruce were used as the primary species for lumber production, the total GWP would be reduced to 178.11 kg CO2 eq. On the other hand, Interfor sawmill is located close to Forks, and the reduction in GWP for using Sitka spruce instead of a heavier wood species mix is not as high as compared to that of Hampton. A noticeable reduction for using Sitka spruce occurs if Interfor sawmill supplies lumber to the CLT mill in Darrington, since the two facilities are further away from each other. In general, in the scenarios where Douglas-fir was used as the primary species, the results show an increase in the total GWP across all sawmills given its high specific gravity.

Table 2.9. Comparison of total GWP of CLT production under different case scenarios based on wood species and travelling distances, excluding transportation of CLT to construction site (unit: 1 m^3 of CLT).

Total GWP (CO_2 eq.)	Douglas-fir/Western Hemlock	Sitka Spruce	Douglas-fir
For Forks CLT Mill			
Hampton	184.81	178.11	185.69
Interfor (Port Angeles)	161.65	160.28	161.83
Sierra Pacific (Aberdeen)	167.15	NA	167.49
Sierra Pacific (Burlington)	184.21	NA	185.06
Weyerhaeuser (Raymond)	169.28	NA	169.68
For Darrington CLT Mill			
Hampton	157.02	156.7	157.06
Interfor (Port Angeles)	177.54	172.5	178.2
Sierra Pacific (Aberdeen)	174.48	NA	175.05
Sierra Pacific (Burlington)	160.7	NA	160.85
Weyerhaeuser (Raymond)	175.65	NA	176.26

Factoring CLT mill location, raw material procurement site and wood species mix, we can state that CLT mills can achieve up to 14% reduction in the overall GWP of the CLT panels by sourcing the lumber locally and using lighter wood species. For instance, the total GWP of the CLT panels, at the Forks CLT mill, produced out of Sitka spruce procured from the Interfor sawmill is 160.28 CO_{2e}/m^3, as compared to that of the CLT panels, produced at the same site, out of Douglas-fir procured from the Hampton sawmill, which is 185.69 CO_{2e}/m^3 (Table 2.9). Similarly, the Darrington CLT mill can reduce the GWP from 178.2 CO_{2e}/m^3 for CLT panels made with Douglas-fir procured from the Interfor mill to 156.7 CO_{2e}/m^3, if they produce CLT out of Sitka spruce procured from the Hampton mill.

2.5. Discussion

The results of this study demonstrate that factors such as location of sawmills, road condition, and wood species mix can play an important role in influencing the total impacts associated with CLT manufacturing. When considering the transportation of CLT, it is important to investigate the appropriate routes for trucks, as well as the geographical condition of the region. Although the direct distance between facilities may appear shorter, they are sometimes divided by regional geographical features (i.e., lakes, rivers, mountains, etc.), which lead to longer transportation routes. Among the five sawmills studied, Hampton sawmill is the closest to the hypothetical CLT mill in Darrington, while the Interfor sawmill in Port Angeles is the closest to the hypothetical CLT mill in Forks. On the other hand, these two sawmills also have the farthest travelling distances to the other CLT mill. This is because the two CLT mills are separated by Puget Sound: Forks CLT mill is on the west of Puget Sound, while the Darrington CLT mill is on the east of Puget Sound. To get to the CLT mill in Forks from Hampton, the vehicle needs to go around the Puget Sound instead of going in a relatively direct route. This adds time and distance to the travel, which, in turn, increases the transportation impacts. Although the linear distance between the Hampton sawmill and Forks' CLT mill may not be the furthest, the actual route condition leads to higher impacts for transporting the same amount of lumber from this sawmill to the CLT mill, as compared to the transportation from other sawmills. The same considerations are valid for the transportation between the Interfor sawmill and the CLT mill in Darrington.

Transportation distance is not the only factor that determines the total impacts of CLT manufacturing. It is important to take into account the type of raw materials used for production.

For instance, the GWP for transporting lumber made of a mix of Douglas-fir and western hemlock from Hampton sawmill to the CLT mill in Forks is approximately 29 kg CO_2 eq., but only 22.5 kg CO_2 eq. for transporting the same amount of Sitka spruce lumber. In some cases, replacing heavier lumber with lighter lumber offsets the impacts posted by longer transportation distance for sawmills located further away. For example, under the baseline scenario where a mix of Douglas-fir and western hemlock is used, the highest impact is produced when using lumbers from Interfor sawmill in Port Angeles for CLT manufacturing in Darrington, in which the GWP can reach 183.3 kg CO_2 eq. per unit of CLT, which is the highest among all five sawmills. If Sitka spruce were used as the primary species for lumber, the total GWP would be 176.94 kg CO_2 eq., lower than two of the sawmills that use Douglas-fir and western hemlock mix. The results of this study suggest that considering the availability of lighter wood species around a lamstock supplier is important from an environmental perspective. Lighter wood species mixes are likely to significantly reduce the overall environmental impacts of CLT production.

The results of this study are consistent with the existing literature. An LCA study of CLT panels produced in Canada indicates significantly lower environmental impacts, as compared to this study (Athena Sustainable Materials Institute 2013). The Canadian study uses a spruce–pine–fir (SPF) mix as lamstock, which is a much lighter wood species mix (~417 kg/m^3). It also reports a significantly lower amount of resin use as compared to the study on CLT production in the U.S. (Puettmann et al. 2018). Further, this study assumed that 100% of the lamstock comes from a single sawmill, whereas, in practice, it is possible to obtain lamstock from different sawmills. It is worth noting that the impacts of different CLT mill capacities were not considered in this study. Changes in mill capacity may lead to further impact variations. Similar to the economies of scale, the production process may become more environmentally efficient on a per-unit basis with an increase in the production capacity.

2.6. Conclusion

This study developed a regionally specific cradle-to-gate LCA for CLT production in western Washington and provided data associated with the potential environmental impacts of establishing CLT mills in two hypothetical locations in the state. The environmental impacts are closely associated with factors such as transportation and wood species mix. Any change in these parameters can influence the environmental impact estimates of CLT production. CLT manufacturing facilities can achieve up to 14% reduction in the overall GWP of the CLT panels by sourcing the lumber locally and using lighter wood species. Even better performance would be expected if the CLT production process was more integrated with the primary lumber production with more access to biofuels.

Given lumber production, forestry related activities and wood transportation play an important role in the overall environmental impact of the CLT panels, access to locally available species and the existing regional harvesting practices is critical in the overall environmental assessment of CLT panels. For the purpose of reducing total environmental impacts, CLT manufacturers need to consider the travelling distance and the type of lumber used for production. In most cases, getting lumber from close-by lumber suppliers can reduce the environmental impacts. Nonetheless, if lumber, or lamstock, suppliers are located in a setting where lighter wood species are available, it may be rational to obtain lumber from these suppliers even if they may be further away.

Non-wood raw materials used for manufacturing CLT can be influential in the overall environmental impact assessment of CLT. Specifically, the amount and type of resin may lead to significant impact variations. For instance, when using lower amounts of resin in manufacturing, the overall impacts of CLT manufacturing is reduced compared to the results of this study (ISO 2017). This study modeled the impacts of CLT based on the use of PUR resin, whereas Puettmann et al. (2018) used melamine–formaldehyde (MF) resin. The difference in chemical composition and production process of the resins are potential factors that can change the impacts of CLT production. The results of this study also show that resin use contributes to 30% of the overall CLT production GWP impacts (29.38 CO_2 eq./m3 of CLT production) and 15–19% of the overall CLT panel GWP impact. Other studies have indicated that the CLT panel can attain the necessary grades by using significantly lower quantity of resin given the CLT volume (Athena Sustainable Materials Institute 2013). Improving the efficiency of resin production and its use in CLT is a key step in limiting the environmental impact of CLT production, which is beyond the scope this study.

Chapter 3: The disposal and landfill emissions of CLT in the construction and demolition waste stream in Washington

The purpose of this chapter is to explore the potential of CLT as a construction material and determine possible disposal impacts from CLT as compared to other materials such as concrete and steel. The application of CLT in the construction industry is influenced by factors such as policy changes, facility availability, and demand trend. This chapter provides an overview of the current waste management status associated with C&D debris in Washington and investigates potential changes in Washington's waste stream. This chapter also estimates potential emissions of CLT from landfill disposal after the end of the buildings' service life.

3.1. Background

End-of-life, or EoL, refers to the phase where the service life of a product ends. For construction materials, the end-of-life phase begins when the construction project is demolished. The end-of-life options for construction materials often include recycle, reprocess, reuse, dispose in landfills, and recover energy (John et al. 2009; Robertson et al. 2012). On top of landfill disposal, one of the most common treatments of wood materials is direct burning as fuel. Other options include recycling and reprocessing for use as raw materials for products such as pellets, pulp, and composite panels. Wood materials not recycled or reused are transported to landfills and often naturally decomposed over time. Emissions can occur in any of these end-of-life options because energy input is required to process, manufacture, and transport the wood materials.

After a building is demolished, its materials become a part of the construction and demolition (C&D) waste stream. C&D debris refers to materials from the construction, renovation, repair, and demolition of buildings, houses, roads, and bridges, etc. and includes a variety of material categories (Bergsdal et al. 2008). Rapid increases in population bring increasing demand for buildings and infrastructure, and it has become likely for Washington to have an increased amount of C&D waste in the future. The treatment of these wastes will bring clear impacts to the environment directly or indirectly. For instance, the quantity and type of wastes disposed will determine the amount of emissions from landfills.

Although the usage phase of buildings is the most energy consuming, as buildings are getting increasingly energy efficient, the end-of-life phase may play a more important role toward the overall energy consumption of construction projects (Dixit et al. 2012; Sandin et al.

2014). As consumption of biomass energy shows growing potential, the end-of-life options of wood materials should be explored more extensively in studies associated with construction and building materials (Gustavsson and Sathre 2006). However, there is a lack of research on the EoL of wood materials. This lack of research could be due to various reasons. For example, it is often difficult to determine wood recovery data because of different demolition practices and the complexity of demolition waste composition (Falk and McKeever 2004; Wiltsee 1998). The treatment or uses of wood materials after demolition is usually overlooked and rarely discussed in detail in previous studies, especially at the local and regional levels.

Separating wood materials after demolition can be difficult and time consuming depending on the diversion practice. In the case of CLT, waste separation may be easier since CLT can be disassembled on-site during demolition. Furthermore, as more construction waste is generated due to population growth, it is likely that waste associated with C&D will show significant increase. Using CLT to replace conventional construction materials such as concrete and steel may reduce the amount of C&D related waste and could potentially reduce the environmental impact of waste disposal. A crucial step in understanding the EoL of CLT, or any other construction materials, is to investigate the status of waste management and the potential impacts of disposal. These factors may include, but are not limited to, quality and quantity of materials, regulations and policies, available facilities and technology, and potential emissions from landfill. Understanding the current waste disposal trend can encourage the adoption of alternative building materials. Knowing the benefits and potential impacts of using CLT can help determine the best feasible EoL options. This chapter explores the role of CLT in waste reduction in Washington and compares the environmental impacts between CLT and other building materials.

An important factor to consider in CLT disposal is the resin. Like many engineered wood materials, CLT requires adhesives to bond the components during production. Although the majority part of CLT panels is lumber, the treatment of adhesives at the EoL stage may directly influence the environmental impact of CLT. Studies associated with emissions from wood resins during the manufacturing and usage stages of wood products are well documented (Baumann et al. 2000; Bohm et al.2012; Guo et al. 2000; He et al. 2012; Sellers 2001; Yu and Crump 1998). However, few studies have focused on the impacts of resin emissions after the wood products are disposed. Common thermosetting resins used in CLT panels include MUF (melamine-urea-formaldehyde) and PUR (polyurethane). Although formaldehyde-free and bio-based adhesives are available, they are not as widely adopted as formaldehyde-based adhesives. CLT panels manufactured in North America have been reported using melamine-formaldehyde (MUF) and polyurethane (PUR) resins (Puettmann et al. 2018; Athena 2013). The type of resin used can directly influence the emissions of CLT disposal and therefore, it is important to take the environmental impact of resin into account.

3.2. C&D Waste Disposal Options

3.2.1. Landfill

In Washington, there are three common types of landfills: municipal solid waste (MSW), limited purpose landfills, and inert landfills. According to the 24th Annual Status Report for solid waste published by the Department of Ecology, there are 14 MSW landfills across

Washington, including 11 publicly owned and 3 privately owned, accepting a total of 5,395,183 tons of wastes in the year 2014. In the same year, limited purpose landfills accepted a total of 619,570 tons of waste, while inert landfills accepted 1,638,252 tons of waste. The amount of waste disposed in landfills has shifted from publicly owned to privately owned landfills since the early 1990s when Washington initially started to collect landfill data. This change is illustrated in Figure 3.1 (Washington State Department of Ecology [DOE] 2015). The two major private MSW landfills in Washington are the Roosevelt Regional Landfills in Klickitat County and the LRI Landfill in Pierce County.

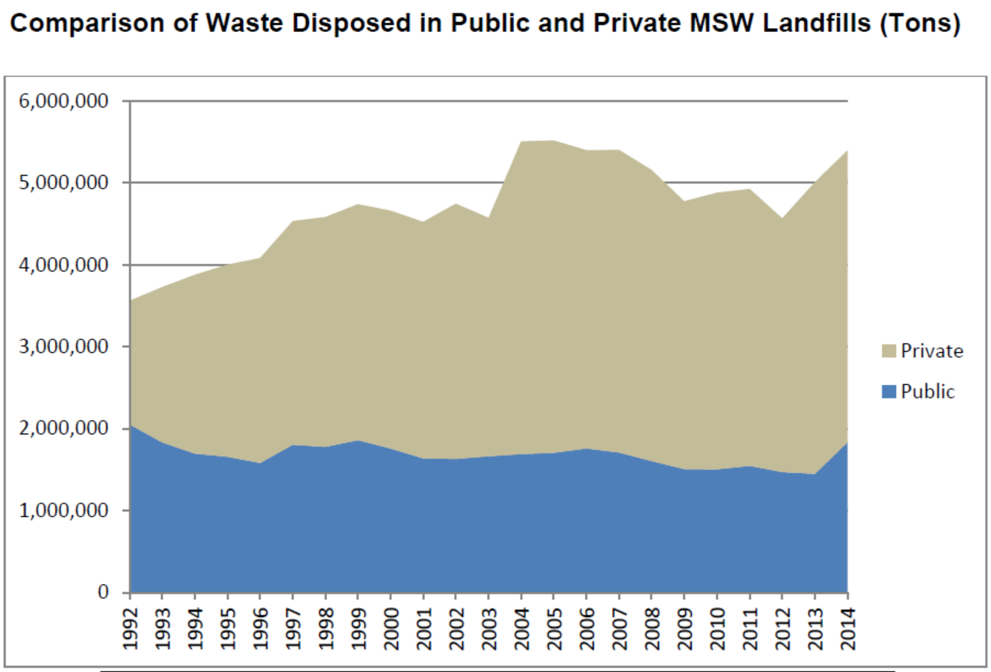


Figure 3.1. Tonnage of waste disposed in public and private landfills from 1992 to 2014 (DOE 2015).

The two other types of landfills in Washington are inert landfills and limited purpose landfills. The requirement and regulations for these landfills is under Chapter 173-350 WAC and Chapter 173-351 WAC. Inert landfills, wood waste landfills and demolition landfills no longer operate in Washington and all wood wastes need to be disposed in either limited purpose or MSW landfill. Inert landfills only accept wastes that are considered "inert", which are wastes that are not reactive and do not decompose. In addition to the three types of landfills described above, Washington also has a landfill type referred to as the ash monofill, which accepts ashes generated from waste-to-energy (WTE) facilities. The Spokane Waste-to-Energy Facility, currently the only waste-to-energy facility in Washington, sent 66,618 tons of ashes from incinerator to the monofill located in Klickitat County (DOE 2015).

Since the early 1990s, the Washington Department of Ecology (DOE) has recorded the amount of waste disposed in landfills and incinerators. The types of waste include MSW, commercial, demolition, medical, inert, and wood. Some counties also accept waste from other states. For instance, Asotin County accepted 25,740 tons of waste from Idaho in 1994. Over the course of ten years from 2004 to 2014, the overall waste disposal amount in Washington increased from 9,082,198 tons to 9,672,226 tons. Among this data, the quantity of construction and demolition (C&D) waste was 1,000,729 tons in 2014, with 617,817 tons in 2010 being the lowest point. This may be due to the economic recession around that time, which affected Washington's housing market. The EPA categorizes C&D debris into six sectors (Schneider 2013), with residential and non-residential demolition accounting for about 50% of all C&D debris on average. Other sectors include residential and non-residential construction and renovation, which together account for the other 50% of C&D debris. The EPA (2016) reported that, on average, the amount of buildings-related C&D material accounts for approximately 30% of all C&D debris, based on the U.S. data collected from 2012 to 2014, whereas roads, bridges, and other structures account for the remaining 70%.

The DOE (2015) estimated the remaining time to capacity of MSW landfills and energy recovery facilities in Washington (Figure 3.2). Landfills in Walla Walla County and Benton County have an estimated time to capacity of less than 5 years and the landfill in Grant County has an estimated time to capacity of 5 to 10 years. Meanwhile, major landfills in other counties still have estimated time to capacities of more than 10 years. Nonetheless, the DOE suggested these facilities have about 324 million tons, or 60 years of capacity, based on the 2014 disposal rate. In other words, if waste generation continues to increase without additional waste disposal reduction or diversion efforts, existing landfills across the state will reach full capacity by 2075.

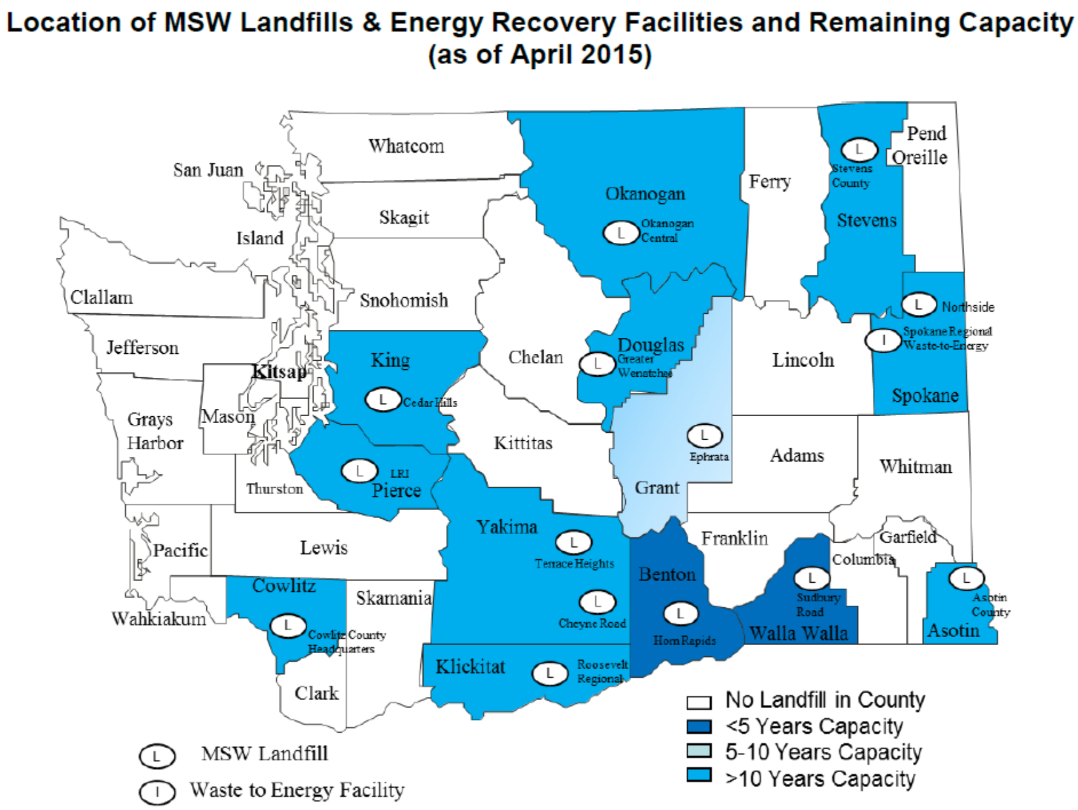


Figure 3.2. Capacities of landfills and energy recovery facilities in Washington (DOE 2015)

3.2.2. Recycle/Reuse

There are many recycling options for C&D debris, especially for wood materials. The most common options are energy recovery, pulp and paper manufacturing, composite boards, and furniture or secondary uses in construction. In metropolitan areas, wood wastes are also used as animal bedding, firewood, and mulch. (Wiltsee, 2008). Washington currently has hundreds of recycling and recovery facilities across the state, with over 150 operating facilities in King County alone. However, not all facilities accept and handle C&D debris and wood wastes, and some of these facilities are small-scale facilities that collect and resale used lumber, but do not process any of the wood wastes. Figure 3.3 shows the amount of wastes recovered for recycling from 2004 to 2014. The total amount of non-MSW waste recovery, including C&D debris, increased from under 3 million tons in 2004 to nearly 4 million tons in 2014, despite a decrease in 2008. The Spokane Regional Waste-to-Energy facility is currently the only permitted waste-to-energy facility/incinerator in Washington.

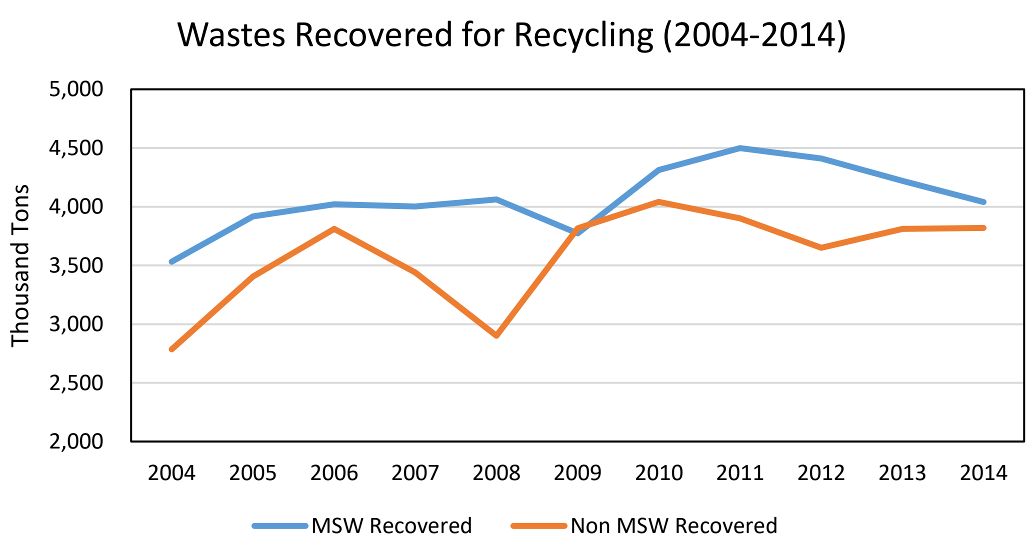


Figure 3.3. Amount of recovered wastes in Washington from 2004 to 2014.

3.2.3. Wood Waste from Construction and Demolition

As an important construction material, wood is used widely for various purposes in buildings, from small components such as window frames and stair cases, to larger components such as flooring and beams. Depending on the type of wood material and its usage, the service life of these woods varies greatly. In general, a typical building may have a service life of 50 to 100 years. While some components such as stairs or doors may need to be replaced during the service life of a building, structural wood materials such as lumber and some engineered woods can have the same service lives as the building (Cochran and Townsend 2010).

The National Renewable Energy Laboratory (NREL) published an estimation of urban waste generation, which suggested the average per capita wood waste generation from C&D is around 0.076 tons/year, with a total waste generation of 0.33 tons, or about 299 kg, per year (Wiltsee 1998). DSM has estimated the average per capita C&D waste generation in the U.S. is about 1.7 lbs per day, or 281 kg per year (DSM Environmental Services 2008). The data was obtained based on a series of surveys conducted in several states, including King County, WA. According to the most recent waste characterization study by DOE (Washington State Department of Ecology [DOE] 2016), C&D related wood materials may include dimensional lumber, engineered wood, treated or painted wood, pallets, and other wood by-products such as saw dust.

In the report by DSM (2008), the wood materials in C&D debris are categorized into seven types: untreated/unpainted wood, pallets and crates, engineered woods, painted/stained woods, pressure-treated, wood furniture, and others. In this report, the average percentage of each type of wood in the waste stream were estimated in King County, WA. Based on these estimates and the Washington C&D waste data provided by the DOE, the amounts of wood materials from C&D debris in Washington from the year 2004 to 2014 were calculated (Figure 3.4). Untreated/unpainted and engineered woods account for approximately 24,752 tons of all wood materials among C&D debris in 2004 and 39,713 tons in 2014.

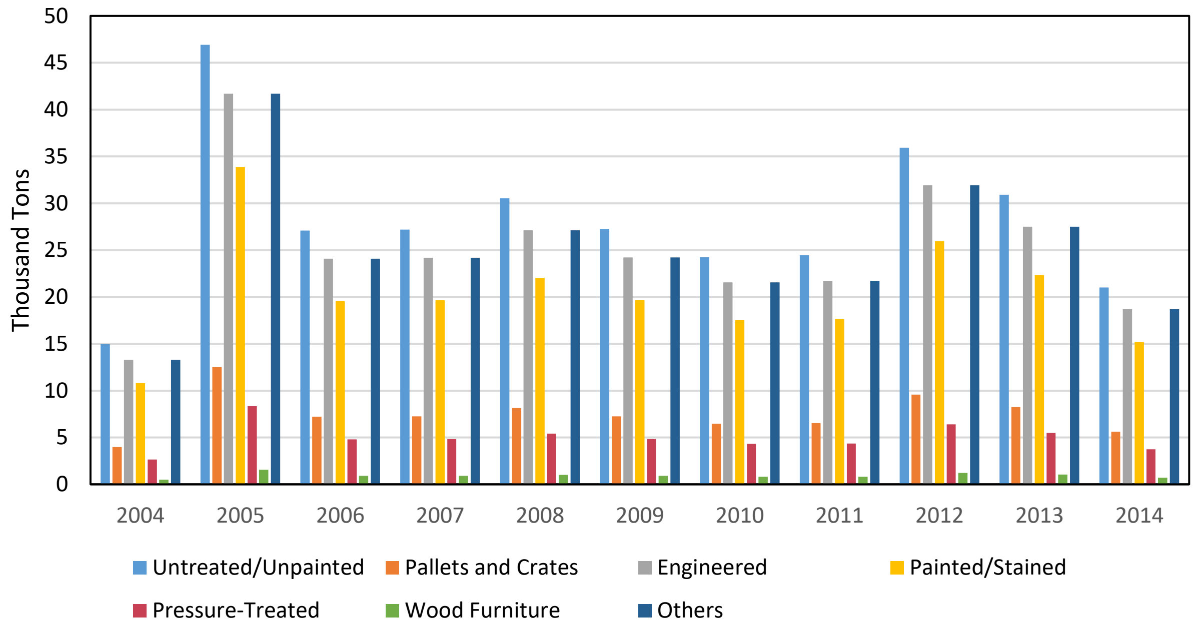


Figure 3.4. Amount of wood materials in the C&D waste stream by category.

The amount of wood related to C&D waste in Washington has varied over the past several years. The Washington Department of Ecology separates C&D related materials into two main categories: disposed and diverted. Disposed materials refer to wastes that end up in landfills, including any C&D debris that is inside or outside the MSW waste stream. Diverted materials refer to those diverted from the landfills for recycling or beneficial uses. While the statewide diversion rate dropped slightly, from 60% in 2009 to 52% in 2013, the wood to energy rate has gone up over the years. The overall diversion rate for C&D related wood waste has gone down slightly after reaching its peaking point from 2008 to 2010. The total quantity of C&D related wood materials has also dropped slightly, from over one million tons in the years 2008 to 2011, to around 950 thousand tons in 2013. Out of all the C&D related wood materials, the proportion of wood used for energy recovery shows an increasing trend, despite the decline in total wood material proportion among C&D debris. Although the rate of wood for energy recovery has declined since its peak in 2009, it has remained above any given year prior to 2009 (Figure 3.5).

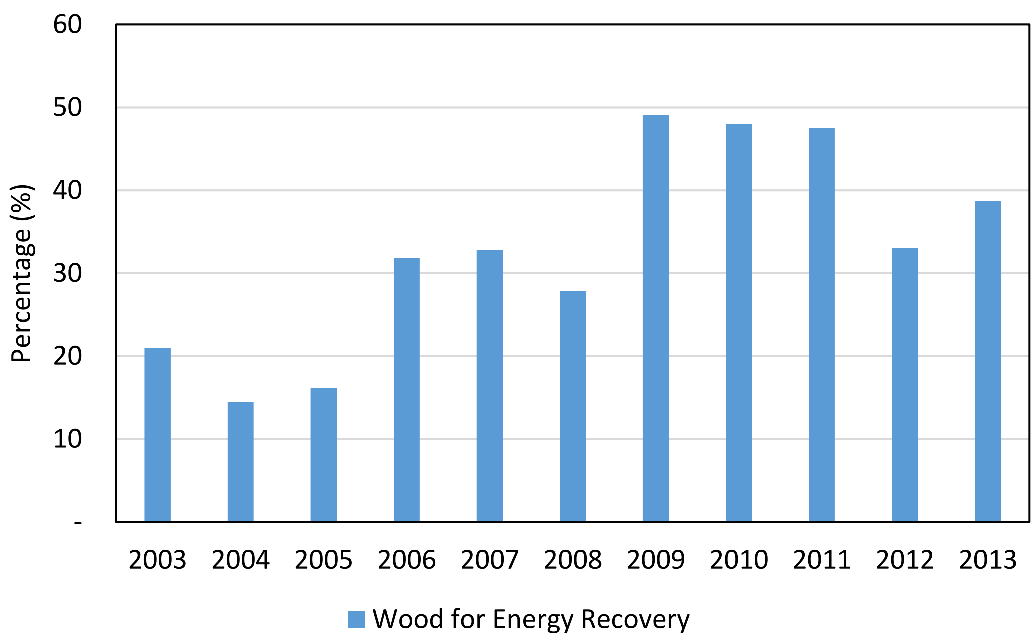


Figure 3.5. Percentage of wood materials used for energy recovery among all C&D related wood waste.

Seattle Public Utilities tracks the quantity and treatment of C&D debris across the city. A recent report showed an increase in the C&D related wood material recycling rate, although the overall recycling rate for C&D debris declined to 57% in 2015 after reaching 64% in 2014, the highest rate since the year 2007 (Seattle Public Utilities 2016). For example, a number of recycling facilities around King County accept wood waste from demolition. The WA Office of Financial Management (Office of Financial Management 2017) reported that Washington experienced an increase of 126,600 persons from 2016 to 2017, representing the largest percentage increase since 2007. The majority of this increase occurred in the five largest metropolitan counties: King, Pierce, Snohomish, Spokane, and Clark, with King County accounting for 38% of the growth. Higher demand for housing is one of the important factors that lead to new building construction projects. For the Puget Sound region alone, a projection of 180,000 new residential homes are needed to accommodate the increasing population, and a 10-year forecast of 240,000 new single and multi-family housing units is projected (Conway 2014). If commercial buildings are included, additional new building projects will take place in the near future. These changes can directly influence the amount of construction material usage and C&D waste generation.

3.3. Potential CLT Waste Associated with C&D

The demand for CLT is likely to follow an increasing inclining trend over the next 20 years (Ganguly et al. 2016). The adoption of CLT in Washington is triggered by various factors, including updated building codes and changes in demographic structure. The city of Seattle updated its building code in 2012 to include CLT, and the 2015 International Building Code includes references to CLT construction (ICC 2015). In 2018, the Washington State Building Code Council According (SBCC) approved the code change that allows the use of mass timber in tall buildings of up to 18 stories. According to the American Housing Survey (AHS) conducted by the U.S. Census Bureau, the percentage of mid to high-rise residential buildings

(buildings with 4 floors or more) has been increasing over the years, especially in urban areas with dense populations. Increasing population and demand for new buildings require efficient construction time. With its fast on-site construction time, CLT building is likely to become more favorable in the future. Figure 3.6 shows the demand potential for CLT in the office building and multi-family building sectors from 2016 to 2035. As described in Ganguly et al. (2016), in the long run, the total area of large office buildings in the PNW is expected to increase by 131 million ft^2, or 12 million m^2, by 2035.

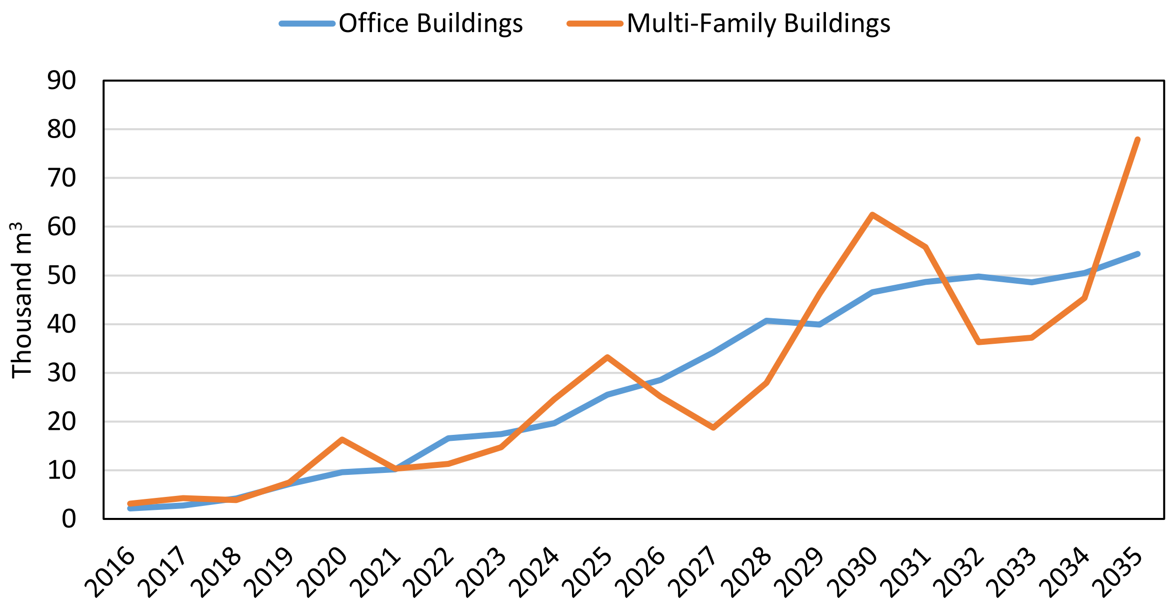


Figure 3.6. Projected growth of CLT demand for office and multi-family buildings.

3.3.1. Policy, Regulations, and Programs Implications

As in any other state in the U.S., there are detailed policies and regulations associated with waste management in Washington. For example, all limited purpose, inert, and MSW landfills are regulated under Chapter 173-350 WAC and Chapter 173-351 WAC, which provide detailed definitions and requirements associated with the design, location, and emission standards for these landfills. Washington has established various regulations and rules in an effort to reduce the greenhouse gas emission from stationary sources. The Clean Air Rule under Chapter 173-442 WAC covers a wide range of businesses and organizations, including power plants, natural gas distributors, petroleum producers and importers, waste facilities, etc. This rule specified ecological actions for those parties covered and requires annual emission reports from these parties. The 2017 threshold under the rule is 100,000 metric tons of carbon emission, meaning that businesses and organizations that emit more than 100,000 metric tons of carbon are covered under the Clean Air Rule and are required to gradually reduce their emissions. The emission threshold is lowered by 5,000 metric tons every three years, and the goal is for the threshold to remain at 70,000 metric tons of carbon emission by 2035.

Under Washington's Clean Air Rule, several landfills across the state are obligated to report and reduce their emissions, including the LRI Landfill in Pierce County and the Roosevelt Regional Landfill in Klickitat County. Landfills in Cowlitz County and Yakima County are also among the list under the rule. The parties listed are assigned a GHG reduction pathway by the Department of Ecology and are required to meet the compliance guidelines under WAC 173-442-060. The actual reduction requirement for each party is outlined by the DOE. Landfills exceeding the threshold are instructed to act based on the DOE guidelines established in 2017.

In addition to statewide regulations, there are also legislative efforts at the county and city levels to reduce emission through better waste management. For instance, Seattle Municipal Code 21.36.089 prohibits the disposal of certain C&D materials in landfills, and sets a citywide 70% recycling goal for C&D by 2020. The code requires all readily recyclable materials, including bricks, concrete, and asphalt from C&D debris to be separated, and these materials are not allowed in garbage containers or disposal sites. Recyclable untreated and unpainted wood materials from C&D should be separated out for on or off site reuse, recycling, and/or beneficial uses. The establishment of such policy guidelines promotes C&D waste reduction.

3.4. Problem Statement

Population growth across Washington State is likely to continue, especially in Seattle and its surrounding environment. DOE's estimated capacity for existing landfills is based on the 2014 waste generation rate. In reality, landfills may reach their full capacity earlier than expected, given the large number of newcomers to Washington and the high number of new construction projects. New establishments of construction projects, including residential and non-residential buildings, bridges, roads, and other infrastructure, are associated with population growth. C&D waste will likely contribute to an increasing amount of waste as these new projects complete, adding burden to waste management across the state. Policies and regulations associated with waste management attempt to address concerns regarding the increasing waste generation rate. Efforts have been made to increase the C&D waste diversion rates to reduce the amount of waste placed in landfills and to promote resources recycling/reuse. Programs promoting recycle and waste-to-energy strategies have been established to meet waste diversion and recycling goals set out by legislatures. There lies great challenges when it comes to C&D waste reduction, especially with the increasing variety of waste sources. Waste reduction goals may be accomplished in many ways, including:

1. Establishing new recycling or waste-to-energy facilities or increasing the capacity for existing facilities, making waste recycling more convenient and feasible.

2. Reducing the amount of materials used during construction
3. Using recyclable and renewable materials to replace materials that are not easy to recycle

Producing CLT and using it as an alternative building material in place of concrete and steel has the potential to meet the waste reduction strategies described above due to its light weight, ability to replace concrete and steel as a building's structural component, renewability, reusability, and uses for energy purposes. Because of the CLT's features and environmental benefits, Washington has taken an interest in establishing CLT manufacturing within the state. However, because CLT is a relatively new product in the U.S., the environmental impacts of CLT at the EoL stage are not well studied.

Further, emission data associated with wood product disposal is lacking. The DOE provides major GHG emission data pollutant data for several landfills in Washington, and the US EPA provides the national average for landfills, but material and substance-specific data are not available. When evaluating the impact on global warming, biogenic emissions are generally not included because of the carbon neutrality assumption. However, since wood tends to decay over time, they can produce significant amount of methane if disposed in landfills. Although methane decays at a faster rate in the atmosphere compared to CO_2, it has a significantly higher warming potential. A major concern with using wood products in construction is that, although wood decomposes slowly in landfill, methane generated from their disposal may still contribute to climate change (Gosline 2014). Knowing the benefit and potential environmental burden of CLT disposal enable us to determine the importance of developing alternative waste treatment options. Investigating the emissions of CLT in landfills is a primary step to determine the best-practice scenario of CLT at the EoL phase.

3.5. Objectives

The remainder of this chapter is divided into two parts focusing on accomplishing the following objectives:

Part 1:

1. Project the potential changes in C&D waste over the next several decades and map the county-level waste generation.
2. Compare materials used in a baseline concrete and a hypothetical CLT/concrete hybrid office building of the same design.
    a. Compare the differences in material requirement of building slabs in both buildings that serves the same structural purpose.
    b. Look at CLT availability for use in new construction projects based on existing literatures.
    c. Investigate potential changes in waste generation by partially replacing concrete and steel with CLT.

Part 2:

3. Create a baseline waste disposal scenario and calculate methane emission.
    a. Calculate potential methane emission from the landfill disposal of CLT under different moisture conditions.
    b. Apply findings for modeling the EoL impacts of CLT using LCA, described in Chapter 4.

3.6. Data and Methods - Part 1: Projection of C&D Waste Generation and the Role of CLT in Waste Reduction

The main use of CLT panels is in construction projects and it is important to understand waste generation trends associated with C&D waste. This section describes data sources and calculation methods for quantifying the C&D waste at the state and regional levels. This section provides estimation and projections of building-related C&D waste and provides a foundation of estimating usage and demolition waste associated with CLT in the future.

3.6.1. C&D Waste Estimation

Data associated with landfill locations and material disposal rate is obtained from the Washington's Department of Ecology. The Washington Office of Financial Management and Seattle Public Utilities provided records associated with population and current recycling rates, which were used as references for estimating the quantity of waste. Method for computing the total waste generation is based on existing literature (Wiltsee 1998; DSM 2008). The weighted average value, 0.9 ton/person/year, is used to project the total C&D waste generation up to the year 2045. Thus, combining the projected population and the per capita waste generation, changes in the quantity of C&D waste generated by each county across the state may be estimated for a given year.

$$W_{county} = 0.9 \times P_{county}$$

Where W_{county} is the total amount of C&D waste in a county in a given year, and P_{county} is the county population of the same given year.

Since the service life of a building ranges from 50 to 100 years depending on the material of the building (O'Connor 2004), a midpoint of 75-year life span was assumed when estimating the future C&D waste generation. A building that is built around 2020 will be demolished in the year 2095. For CLT panels used in construction as structural panels around 2020, this estimation assumes these materials have a ~75-year service life, same as the buildings' service life. In this case, the C&D debris in 2095 will likely include CLT panels. Since population estimation data in Washington is not available at this point, the C&D waste generation weight is estimated using the projected annual population from 2005 to 2015. The 2015 population data is used as the baseline population to estimate the 2095 population across the state, and the C&D debris generation is obtained based on the estimated 2095 population.

3.6.2. Incorporating CLT in the C&D Waste Stream

Based on data of various existing building designs and hypothetical design models for CLT buildings, the material quantities of CLT and other building materials were calculated. A mid-rise reinforced concrete office building is used as the reference building, and a hypothetical building of the same architectural design is modeled to calculate the material quantity required for CLT. Data details may be found in Simonen et al. (2018). The material quantity of the two buildings are compared to determine the potential amount of CLT use in the future. CLT replaces some, but not all, of the concrete and steel materials used in the concrete building. For example, the slabs in the concrete building consist of only concrete and steel, and the slabs in the hypothetical wood prototype building are made with CLT (20%), concrete (60%), steel (2%), and gypsum wallboard, or GWB (18%). By comparing the material quantities for CLT and reinforced concrete buildings with identical design, the material quantity of CLT and concrete for particular structural elements may be calculated. Since the density of CLT is different from concrete or steel, the material quantity required to build a CLT slab differs from that required for a concrete and steel slab that serves the same structural purpose.

Based on Simonen (2018), the material quantity required for a slab in a typical office building made of concrete and steel is approximately 5.1 million kg. To compare the material quantity of CLT and concrete, one office building has a concrete/steel only slab, while a hypothetical building of the same design uses CLT to partially replace some concrete and steel materials used in slabs. The general mass ratio of CLT slabs and concrete/steel mixed slabs is 1:2, meaning 1 kg of the materials required with CLT replacement can serve the same structural purpose of 2 kg of the materials required for concrete/steel slabs. All materials required for installing CLT slabs (i.e. steel connections and GWB, etc.) are included. For the whole building, the total mass ratio of an office building with CLT substitution and an office building without CLT substitution is approximately 1:1.5. The amount of CLT used in buildings is assumed to be the same as described in Simonen et al. (2018).

The adoption of CLT is likely to increase over time, according to the demand study by Ganguly et al. (2016). By knowing the quantity of CLT that may be available in the future, material quantities for buildings with and without substitution of concrete with CLT can be estimated. For example, the materials used in a building with partial CLT substitution are lighter in mass compared to a building without any CLT. If the availability of CLT meets the projected demand trend, potential material reduction can be calculated by using the material quantity ratio for buildings with and without CLT substitution.

3.7. Results for Part 1

3.7.1. Changes in C&D Waste Quantity

Figure 3.7 illustrates the current C&D waste disposal rate for each county in Washington and the quantity of C&D materials in major landfills across the state based on the 2014 data. Note that waste disposal quantity only accounts for waste that is disposed in landfills and does not equal waste generation quantity. The actual waste generation associated with C&D is shown in the Figure 3.8. As shown in Figure 3.7, the largest MSW landfill is located in Klickitat County, and the largest limited purpose landfills are located in Yakima and Spokane. Western Washington does not have large-capacity landfills, but there are several moderate sized landfills in Pierce, Cowlitz, and Grays Harbor. As for waste generation, King County has the highest quantity of C&D debris disposal and is the only county in WA that disposes of more than 250,000 tons of C&D waste. King County is followed by Snohomish County, and then by Pierce, Yakima, and Spokane. These five counties account for most of the C&D waste disposal in WA. The actual C&D waste generation is higher since Figure 3.7 only shows the amount of C&D waste disposed in landfills.

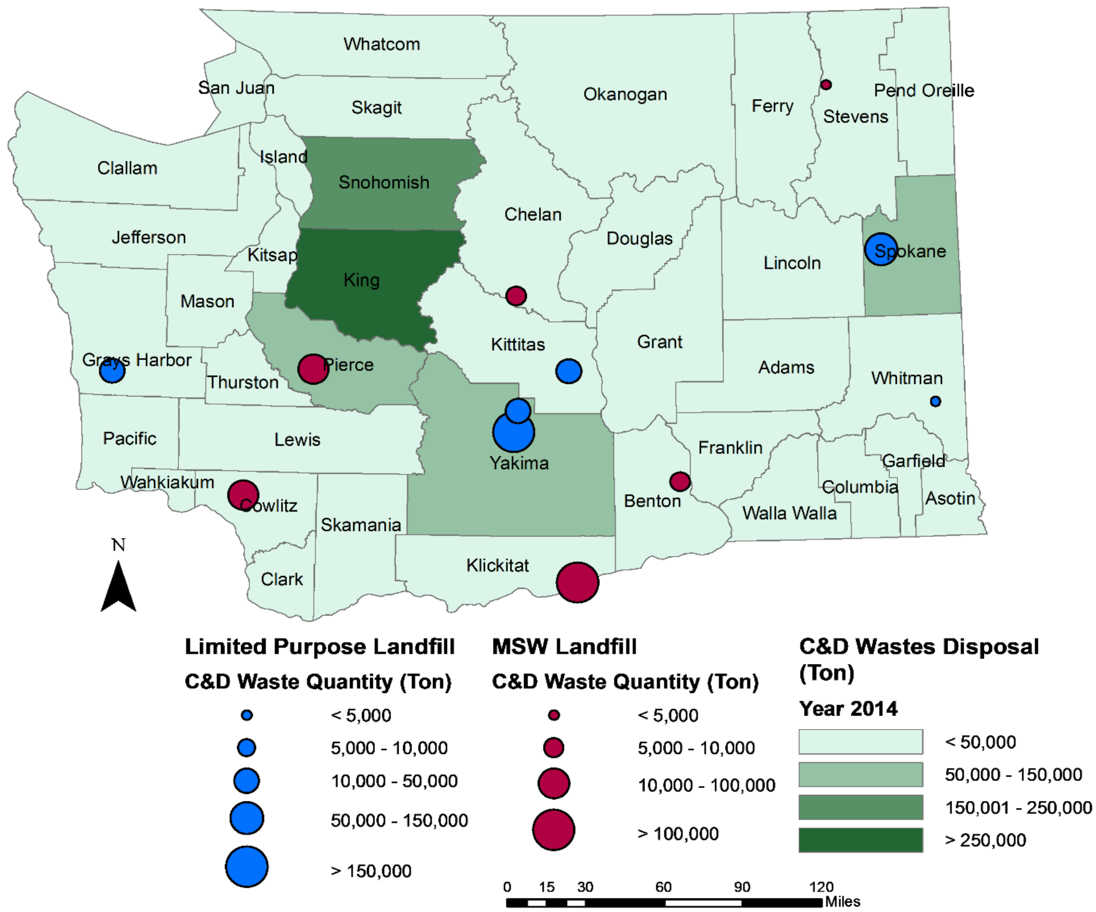
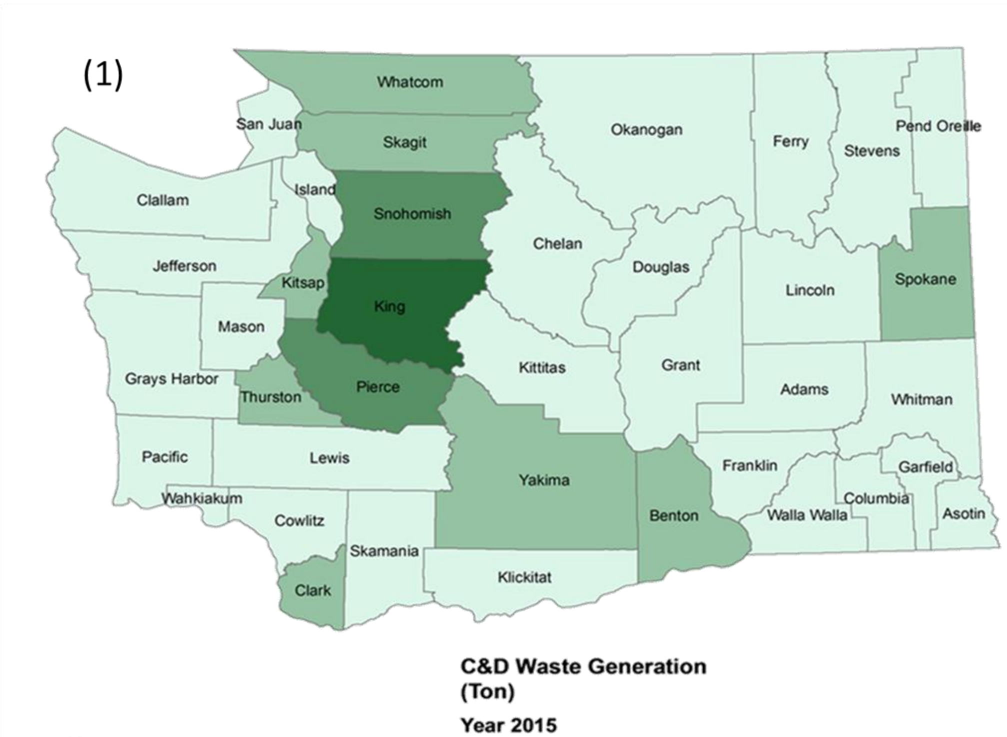


Figure 3.7. Amount of C&D waste disposal and the distribution of landfills in Washington in 2014.

Figure 3.8 illustrates the changes in C&D debris quantity in each county from 2015 to 2045. The 2045 data is based on the population projection by Office of Financial Management. In 2015, most of the counties generated less than 100,000 tons of C&D debris and King County is the only county that generates more than one million tons of C&D debris. By the year 2045, at least one other county, Pierce County, will generate more than one million tons of C&D debris. Other counties will show an increasing trend in C&D debris generation. Spokane and Clark generated between 100,000 to 500,000 tons of C&D related waste in 2015, but by 2045, each of the two counties generates more than 500,000 tons of C&D waste. Moreover, the counties of Cowlitz and Grant also showed clear increases in C&D related waste generation.

By 2095, which is around the time when many of the buildings undergoing construction right now will reach the end of their service life, the estimated C&D debris in almost all counties shows a clear increasing trend. As shown in Figure 3.8(3), over half of the counties in Washington will generate at least 100,000 tons of C&D debris and 9 out of 39 counties will generate at least 500,000 tons of C&D debris. King County will no longer be the only county with more than one million tons of C&D debris. Spokane County and Clark County have already shown clear increasing trends in 2045 and will become two of the five counties that generate more than one million tons of C&D debris. If population continues to grow at the current estimated rate, Snohomish, Pierce, and King will continue to be the three most populated counties and therefore generate the largest amount of C&D debris by weight.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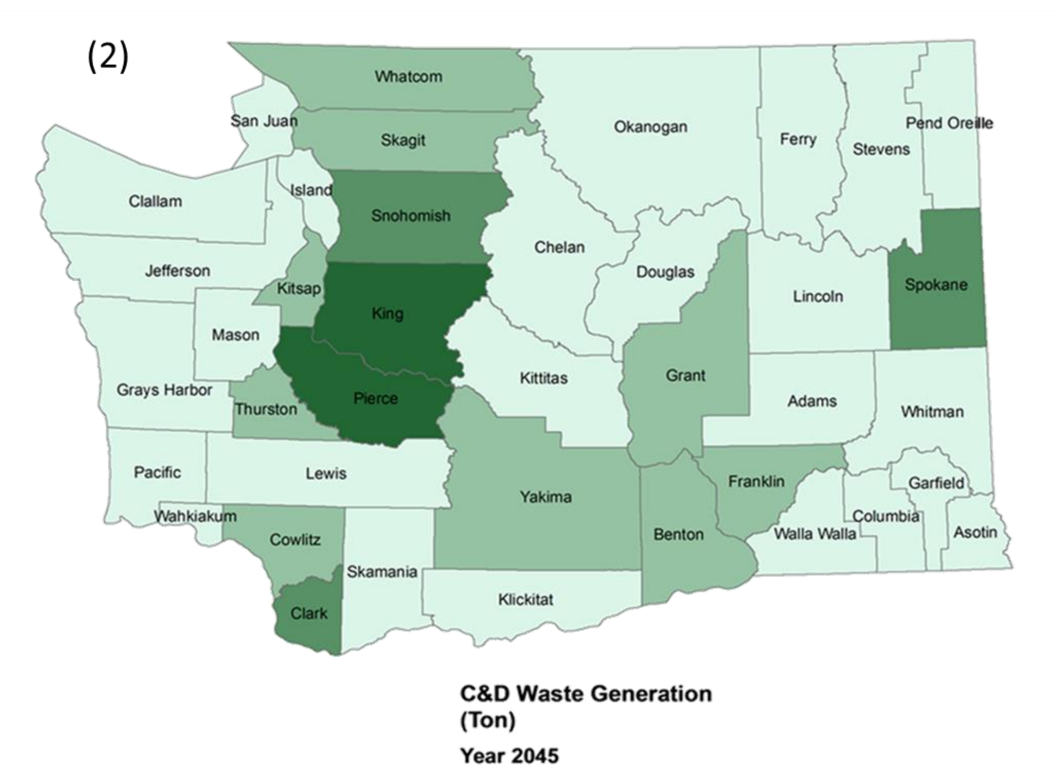
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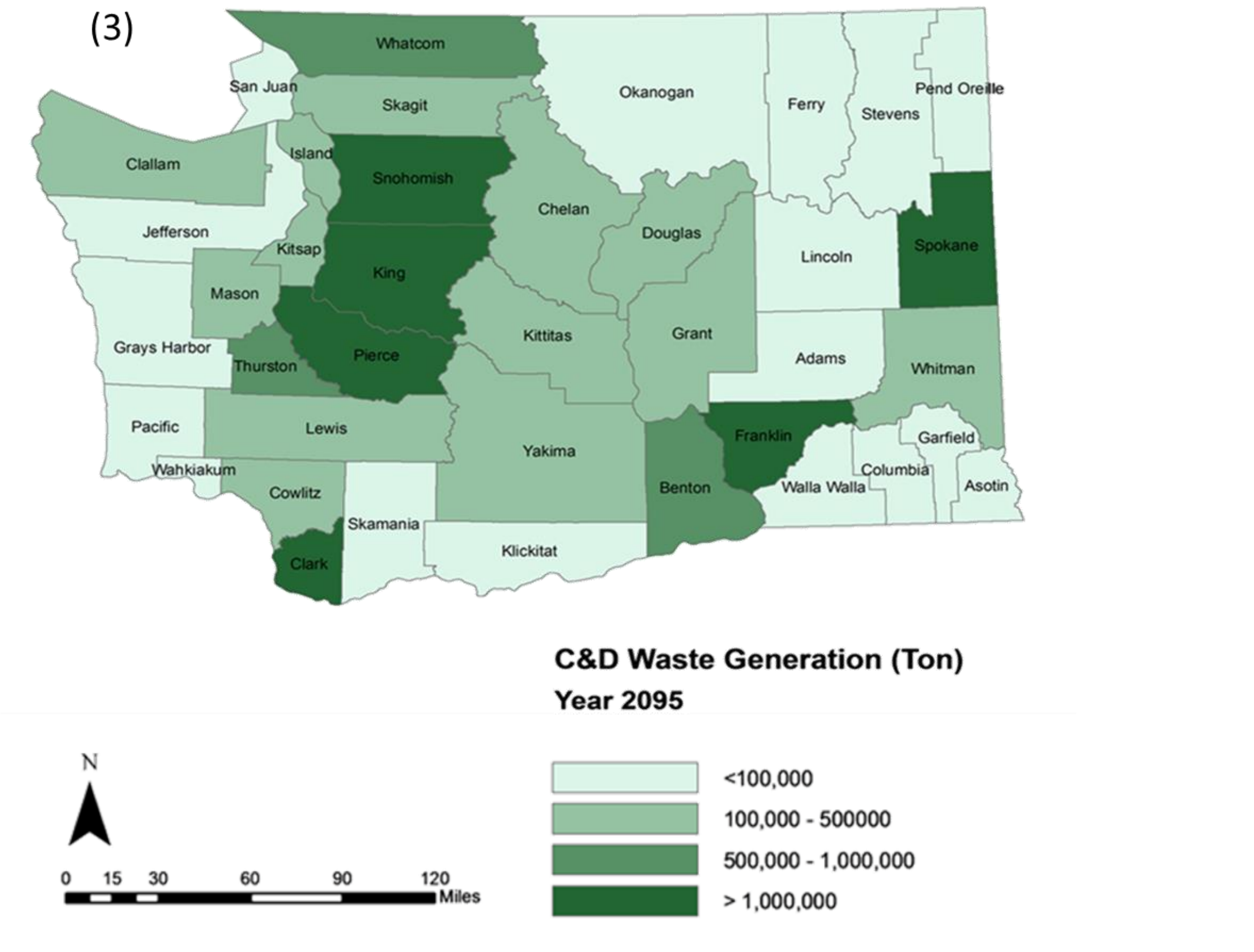


Figure 3.8. C&D waste generation by year and county: (1) C&D waste generation across Washington in 2015, (2) Projected C&D waste generation in 2045, and (3) Projected C&D waste generation in 2095.

3.7.2. CLT in the C&D Waste Stream

As the most populated county in Washington, any changes in the waste stream of King County can directly affect the entire state as a whole. King County also houses the city of Seattle, one of the fastest growing cities in the US. As the population in King County continues to grow, the amount of building-related C&D debris is likely to increase. The results described in this section are for the city of Seattle as it is one of the most important metropolitan areas in western Washington and represents large proportion of new construction across the PNW.

Assuming the rate of CLT substitution increases with CLT availability, the materials required for building slabs are reduced if CLT substitution takes place. By 2035, available CLT can be used in nearly 50 new buildings slabs, requiring a total of 127 million kg of materials. If only concrete and steel slabs are built, nearly 250 million kg of materials will be required to build the same number of buildings. In a concrete/CLT hybrid office building, there will be around 123 million kg reduction in waste associated with new building constructions.

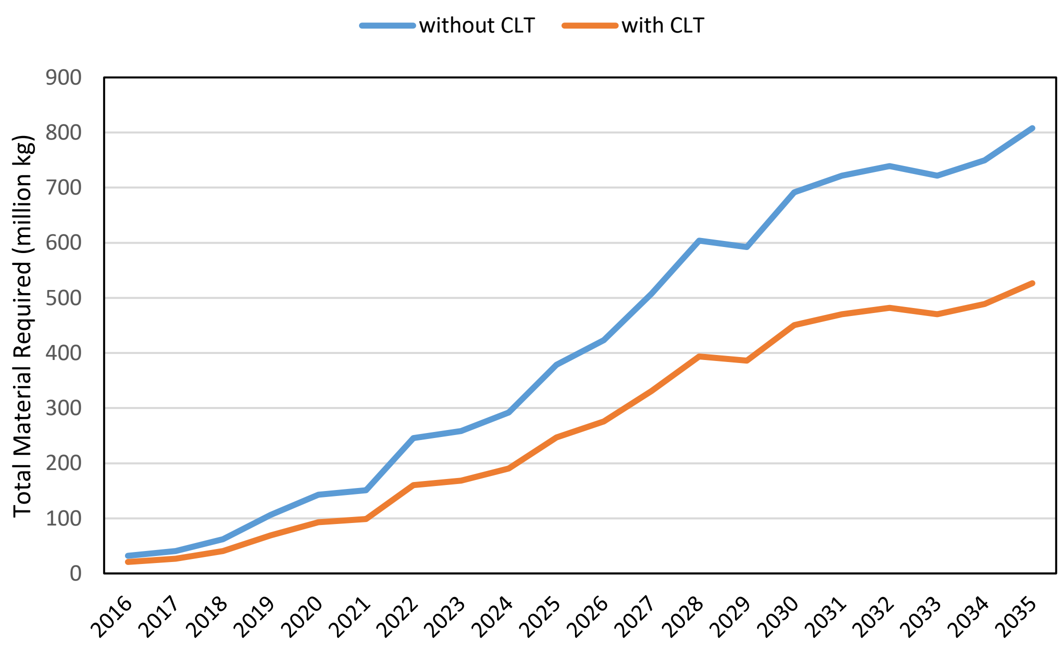


Figure 3. 9. Material required for the same number of new constructions with and without CLT substitution.

From a whole-building perspective, buildings with CLT substitution require noticeably less material than buildings without CLT substitution, and the difference in material quantity expands as more CLT becomes available for construction (Figure 3.9). In 2020, for the same number of buildings, substituting a proportion of concrete and steel with CLT keeps the total mass of materials at around 93 million kg, whereas 143 million kg of materials are required if there is no CLT application. This creates a 50 million kg difference in materials. By 2035, this difference will increase to 281 million kg.

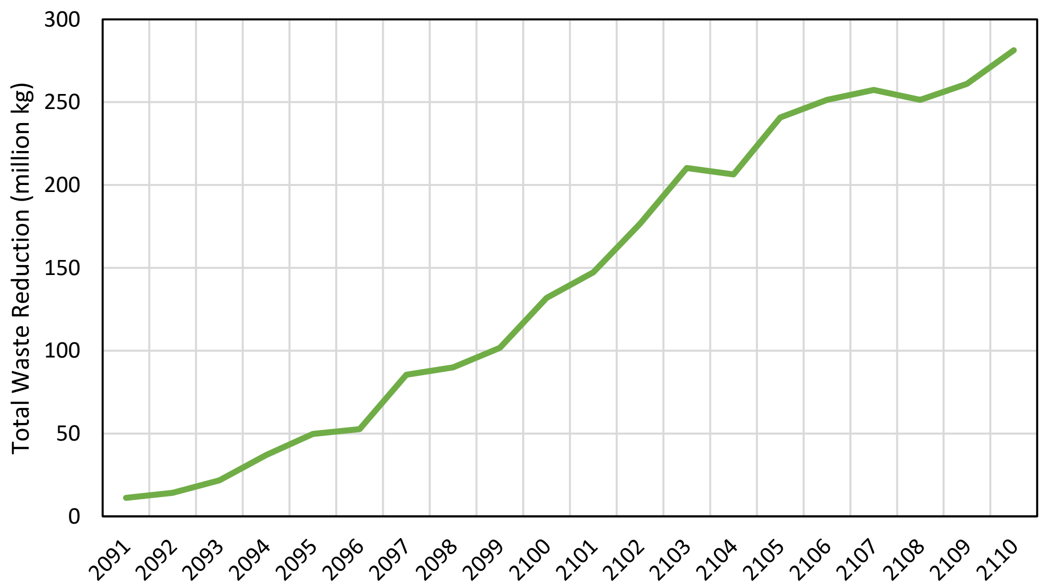


Figure 3.10. Demolition waste reduction by implementing CLT substitution in constructions.

The reduction in material requirement can lead to reduction in waste at the time when the buildings are demolished, as shown in Figure 3.10. For example, assuming office buildings have an average service life of 75 years, buildings constructed in 2018 will be demolished in 2093. If some of the materials in the buildings built in that year are replaced with CLT, this will generate about 22 million kg of waste in 2093.

If CLT adoption increases over the next 20 years, CLT will be able to help reduce the amount of building-related C&D debris in the future. As the adoption of CLT increases, waste reduction is likely to increase as well.

3.8. Data and Method - Part 2: Estimating the Emissions from the Landfill Disposal of CLT

This section estimates of the emissions from disposal. The emissions are estimated based on a baseline scenario where all CLT are disposed in landfills. This section focuses on estimating the emission of CLT in landfills, and applying the results to the structural components of a building.

3.8.1. Methane Emissions from CLT

A key step in assessing the environmental impacts of CLT during the EoL stage is to estimate the emissions generated from different waste treatment options. The total GHG can be calculated by multiplying the total amount of CLT (M_{CLT}) by the sum of the emissions of each GHG (E_i) over a given time frame:

$$Emission = M_{CLT} \times \sum_i E_i$$

Major GHGs generated from landfills include CH_4 and CO_2, which are also major substances involved in climate change. This research estimates the emission factor of these substances and evaluates the overall impacts of CLT panels under different disposal scenarios.

Methodology for estimating landfill emissions described in the EPA documentation (EPA 2015) and used data generated from a series of studies associated with waste decomposition behavior (Barlaz 1998; Cruz and Barlaz 2010; Eleazer et al. 1997; Wang et al. 2011; Wang et al. 2013). The EPA uses this method for its Waste Reduction Model (WARM). The focus of this model is MSW, and thus, it does not provide specifications of the emission contributions from different substances, nor does it provide focus on demolition waste. This research refers to the method described in EPA (2015) and applies this method to calculate the emission factors from CLT panels at the EoL stage.

Several factors are considered when calculating emissions from landfills, including the decay rate of wastes, moisture condition of the landfills, and landfill gas (LFG) collection practices. This methodology accounts for four main components that influence the emission: 1) initial carbon content of the material, 2) carbon output as CH_4, 3) carbon output as CO_2, and 4) residual carbon, which refers to the carbon remained in the landfill as carbon storage.

Output of CH_4 and CO_2 from disposed CLT in landfills is closely associated with the quantity of carbon content. As a wood product, CLT is biodegradable and emits CH_4 after disposal. The quantity of CH_4 emission from CLT depends on the landfill condition and the proportion of carbon emitted as CH_4. The chemical composition of wood is mainly cellulose, hemicellulose, and lignin (Chen 2014; Pettersen 1984; Wang et al. 2013). The ratio of CH_4 and CO_2 generation from initial carbon from hemicellulose refuse is assumed to be 1:1 in a simplified system where they are the only substances produced from initial carbon (Barlaz et al. 1989).

The methane emission is calculated over a 100-year time frame, after which the methane emission is assumed to be very close to zero. The first-order (FOD) decay model is widely used to estimate landfill emissions and will also be applied in this research. Based on the models suggested by IPCC (Intergovernmental Panel on Climate Change [IPCC] 2000), the total CH_4 emission in year x may be determined by using the methane generation rate of CLT (k) and the CH_4 generation potential of CLT wood, L_0. The recovery rates are obtained based on EPA's background documentation by (Levis and Barlaz 2014). The emission from adhesives contained in CLT panels is not included in this estimation, but will be described later in this chapter. The total methane emission in a single year may be expressed as:

$$E_{CH4} = \sum A \times k \times M_x \times L_0 \times e^{-k(T-x)}$$

The total emission of CH_4 in year x (E_{CH4}) is estimated based on the potential CH_4 generation (in m^3/Mg) from CLT (L_0), the current year (T), and the methane generation rate (k). The symbol A is the normalization factor for adjusting the year to a continuous variable. Landfills in many regions implement landfill gas (LFG) recovery practice. The following formula is used to account for LFG recovery and oxidation rate (Cai et al. 2014; Intergovernmental Panel on Climate Change [IPCC] 2000). In this study, the LFG collection efficiency assumption under "typical collection" scenario is adapted from EPA (2015), which assumes 68.2%, 65%, 64.1%, and 64.8% under dry, moderate, wet, and average landfill moisture conditions, respectively. The oxidation rate varies depending on the methane flux. An oxidation factor represents the amount of methane oxidized in the soil that covers the waste in landfills. Although the default value suggested by the IPCC (2000) is 0, it also suggested that an oxidation factor of 0.1 is appropriate in well-managed landfills. Only methane that is not captured is subject to oxidation, and thus, the recovered methane is subtracted prior to the presence of the oxidation factor:

$$E_{CH4} = \sum A \times k \times M_x \times L_0 \times e^{-k(T-x)} \times (1 - R) \times (1 - OX)$$

Where:

R: CH_4 recovered through landfill gas collection practice

OX: Oxidation factor

The wood component of CLT is assumed to decompose over time. The CH_4 generation potential of CLT (L_0) is based on the amount of material disposed, the fraction of degradable organic carbon, the fraction of organic carbon that decomposes, and the fraction of CH_4 generated among landfill gases. The approximate component-specific percentage of CH_4 as a proportion of the initial carbon is based on the studies by Wang et al. (2011), Wang et al. (2013), and Levis and Barlaz (2014). The number for dimension lumber is used for estimating the CH_4 generation potential from CLT (L_0). This research also adjusted the percentage by cross-validating with previous studies by Cruz and Barlaz (2010) and Eleazer et al. (1997) and determined the amount of CH_4 yield (L_0) is approximately 14 m^3 per 1 Mg, or 0.014 m^3 per 1 kg, of lumber. Therefore, the above equation for L_0 may also be expressed as a function of the weight of the wood portion of the CLT panels disposed in year x:

$$M_x \times L_0 = M_x \times 0.014$$

Where M_x is the weight of CLT panels, and 0.014 is the potential CH_4 generation for the wood portion of CLT. The density of methane gas is assumed to be 0.668 kg/m^3, thus, L_0 may be converted to kg by multiplying the density.

The quantity of substances generated from landfills is closely associated with the methane generation rate (k) of the wastes due to a series of chemical reactions occurring during decomposition. The rate of methane generation depends on the type of material and the moisture content of the landfill. Five levels of moisture content are used. The general k values corresponding to each of the moisture conditions is described and illustrated in Figure 3.11 (Cruz and Barlaz, 2010; EPA 2015):

1. Dry: Landfills receiving fewer than 20 inches of annual precipitation ($k = 0.02/yr$)
2. Moderate: Landfills receiving 20 to 40 inches of annual precipitation ($k = 0.04/yr$)
3. Wet: Landfills receiving more than 40 inches of annual precipitation ($k = 0.06/yr$)
4. Bioreactor: Landfills operating as bioreactors. Water is added until the moisture content reaches 40% moisture content on a wet-weight basis ($k = 0.12/yr$)
5. National Average ($k = 0.052/yr$)

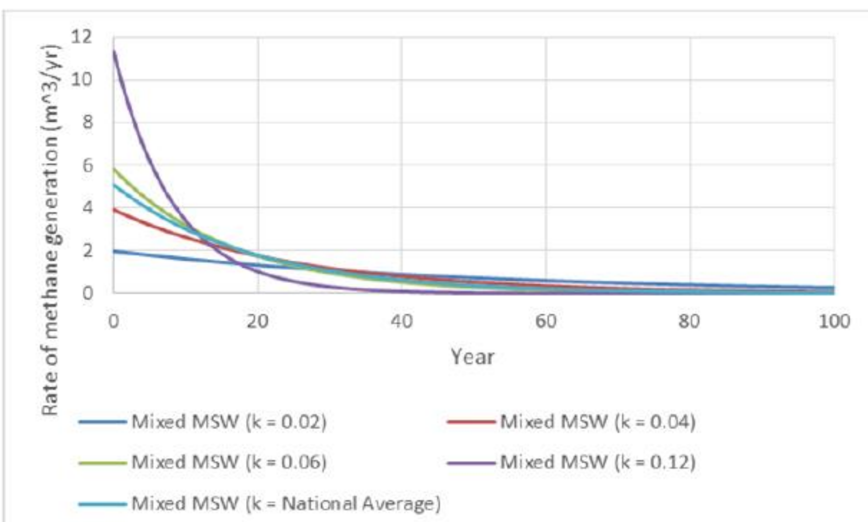


Figure 3.11. Example of methane generation rate under different landfill moisture conditions over 100 years by using the decay function (EPA 2015).

Based on the k values, CH_4 emission factors from landfills in different regions may be calculated. For example, landfills in western Washington may have higher moisture content compared to those in eastern Washington. Therefore, different k values will be applied to calculate the emission factor for methane, depending on the region where the CLT material is disposed.

3.8.2. Other Emissions from CLT

Emissions for additional GHGs, as well as chemical compounds associated with climate change, acidification, eutrophication, and human health, etc., are estimated using the Ecoinvent version 3 database. The Ecoinvent database is developed by the Swiss Centre for Life Cycle Inventories and contains life cycle inventory datasets for a wide variety of human activities. The Ecoinvent database has been updated recently to include inventory data in addition to European data. Inventory data for waste treatment such as landfill and incineration processes are included. Methodology used for Ecoinvent database are described in (Weidema et al. 2013). The method used for analysis is TRACI 2.1/US 2008.

3.8.3. Emissions from Adhesives

The impacts of amino-based resins is evaluated in addition to the wood portion, as it is an important component in CLT panels. There are a variety of adhesives used in CLT, including MUF (melamine urea formaldehyde), PF (phenol formaldehyde), PRF (phenol resorcinol formaldehyde), and PUR (Polyurethane). Although formaldehyde-based adhesives are still the most commonly used adhesives around the world, PUR has gained its place recently, especially in the engineered wood products industry and it is the primary choice of adhesive used in CLT

(Messmer 2015). Since adhesives are rarely separated from the wood and usually stay in the CLT panels at the EoL stage, the emissions from adhesive can influence the overall environmental impacts of CLT panels. Emissions from PUR include methane and carbon dioxide, as well as a variety of toxic substances. The Ecoinvent database is used to assess the impacts of PUR adhesives and the results will be added to the total impacts of CLT, which is described in detail in the next chapter. Emissions from PUR used in CLT panels is estimated using inventory data associated with polyurethane in plastics since the primary composition are similar.

3.9. Results for Part 2

As described in the previous sections, the reduction in construction waste can lead to reduction in emission from waste disposal. This section focuses on the impact of landfill disposal of CLT. As the main landfill emission, the emission factor of methane is the primary focus and is calculated and applied to CLT panels. With limited prior knowledge of the emissions of CLT panel disposal in landfill, methane emission factor is calculated under different landfill moisture and LFG recovery conditions to provide a more comprehensive result.

3.9.1. Methane

As shown in Figure 3.12, under dry, moderate, wet, and the U.S. national average moisture conditions, the methane emission from CLT panels emits at different rates. Under wet condition ($k = 0.06$), methane emission occurs mostly in the first 25 to 50 years and decreases afterwards. Under moderate moisture condition ($k = 0.04$), CH_4 emission continues at an observable rate until 75 years after initial disposal. CLT panels in landfills under dry condition

($k = 0.02$) generate the lowest total CH_4 emission over the 100-year timeframe, but it takes more time for the materials to decay. CLT in landfills under wet condition generates the highest amount of CH_4 at the beginning as the materials decays faster, and the trend becomes relatively constant after 60 years. Under all moisture conditions, CH_4 emission from CLT panels' wood portion will eventually decline to a very low rate after 100 years.

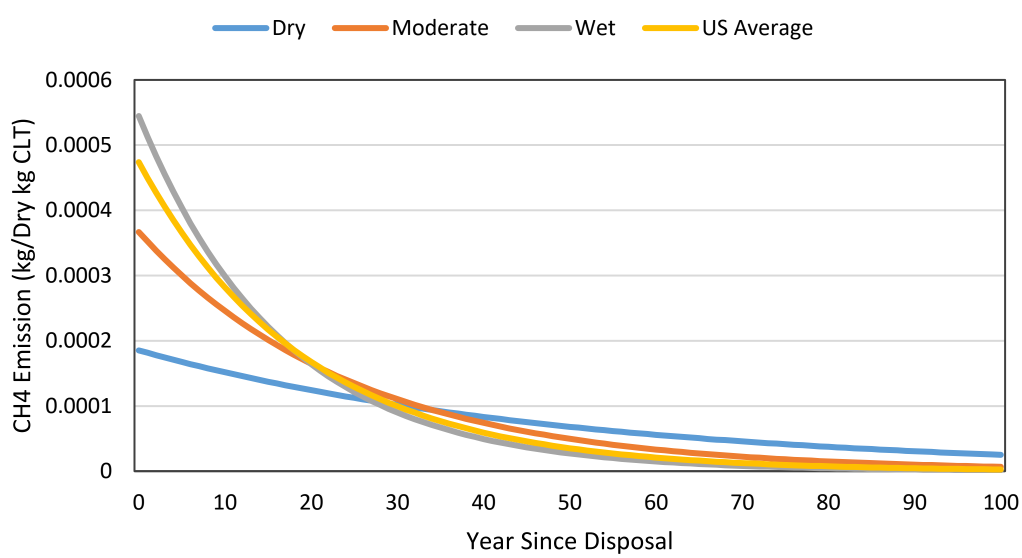


Figure 3.12. Methane emission for 1 kg of CLT wood over 100 years under dry, moderate, wet, and average landfill conditions.

If LFG collection is taken into account, CH_4 generation will decline under all landfill moisture conditions. Figure 3.13 presents the total CH_4 emission of 1 dry kg of CLT panels under different moisture conditions with or without LFG collection for energy. Methane recovery rates were based on the calculation by Levis and Barlaz (2014). Under dry condition, total CH_4 emission decreased from 0.00811 kg per 1 kg of CLT to 0.00232 kg when accounting for methane recovery. Total CH_4 emission decreased from 0.00918 kg to 0.00289 kg and from 0.00933 kg to 0.00301 kg under moderate and wet landfill conditions, respectively. Under the

U.S. national average moisture condition, total CH_4 emission decreased from 0.0093 kg to 0.00295 kg per 1 kg of CLT wood. The result showed approximately 70% reduction in total CH_4 emission under all moisture conditions over a 100-year period.

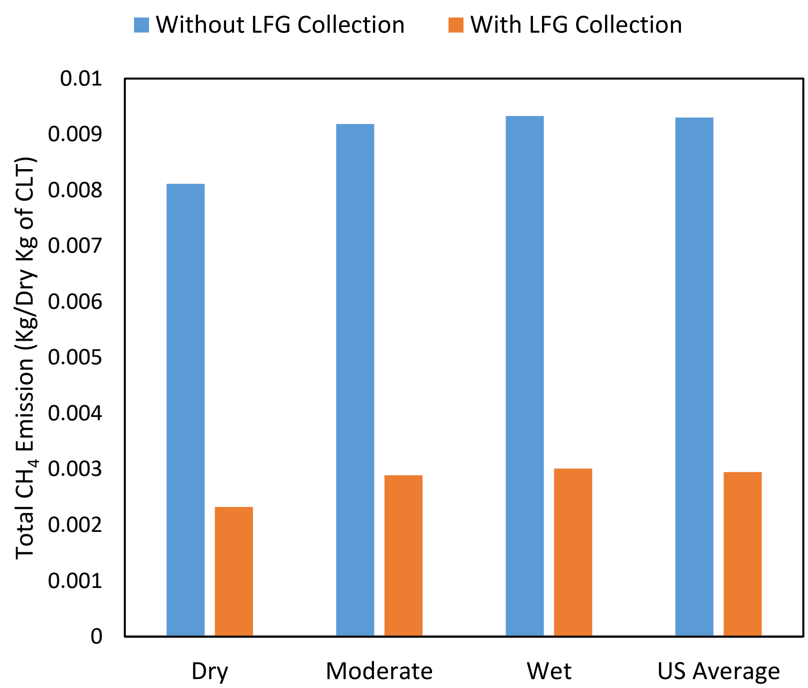


Figure 3.13. Comparison of the total methane emission for 1 kg of CLT wood over 100 years with and without LFG collection practice.

3.9.2. Other Emissions

Although the main emissions from disposed wood products are methane and CO_2, many other chemicals contribute to the overall environmental impacts of CLT panels. Using inventory data from the Ecoinvent database, GHGs and other traced substances from 1 kg of CLT disposal is presented (Tables 3.1 and 3.2). The wood portion accounts for 98.6% of 1 kg of CLT panels, whereas resin accounts for 1.4%. CO_2 from wood is considered biogenic. Other major substances include nitrogen oxides (NO_x) and phosphorus, etc. In addition to emissions from the wood portion of CLT, emissions from one kilogram of polyurethane-based resin are shown partially in Table 3.2. Detailed tables for all emissions are shown in the appendix. Carbon emission from the wood portion of CLT panels is considered biogenic.

Table 3.1. Main emissions from the wood portion of 1 kg of CLT.

Substance (Wood from 1 kg of CLT)	**Unit**	**Total**
Carbon dioxide, biogenic	kg	0.016
Nitrogen oxides	kg	7.69E-05
Phosphorus	kg	1.28E-08

Table 3.2. Main emissions from the resin portion of 1 kg of CLT.

Substance (Resin from 1 kg of CLT)	**Unit**	**Total**
Carbon dioxide, fossil	kg	0.00045
Methane, fossil	kg	3.5E-05
Nitrogen oxides	kg	1.46E-06
VOC, volatile organic compounds	kg	1.12E-06

Considering slabs serving the same structural purpose, a slab in the concrete building requires 5.1 million kg of materials, whereas a slab in the building with CLT only requires 2.6 million kg of materials. Assuming all steel materials in the slabs (i.e. rebar, connections) are recycled and not disposed in landfills, the emissions from slabs with CLT panels are shown in

Table 3.3. The total CO_2 emission of using CLT slabs is 22,915 kg. It is important to note that 8,359 kg of CO_2 are from the wood portion in CLT, which are considered biogenic and does not contribute negative environmental impacts because of the carbon neutrality assumption. If fossil CO_2 are accounted, slabs with CLT only produce 14,556 kg CO_2, mainly from resin, GWB, and concrete.

Table 3.3. Comparison of building slabs serving the same structural purpose. The slab in the hybrid building contains CLT, while the slab in the concrete building does not contain CLT

	Unit	**With CLT Replacement**
Carbon dioxide, biogenic	kg	8,359
Carbon dioxide, fossil	kg	14,556
Nitrogen oxides	kg	111

3.10. Discussion

3.10.1. C&D Debris Generation Trend

The results indicate that Washington has made an effort to improve C&D waste treatment methods through diversion and recycling, and more C&D related wood materials are used for energy recovery. Nonetheless, more efforts are needed to meet the waste reduction goal and to overcome emerging challenges associated with population increase. The overall C&D debris generation across the state shows a clear increasing trend. In 2015, King County is the only county in the state generating more than one million tons of C&D waste, while most of the counties generate less than 100,000 tons of C&D waste. Assuming the type and quantity of construction materials remain the same, by 2095, King County alone will generate over 5 million tons of C&D waste. The rate of development and changes in demographic structure are important driving factors of C&D waste generation. A younger demographic structure tends to increase demand for multi-family buildings and industrial development increases the demand for office buildings in metropolitan areas.

The results of this chapter show a clear trend of C&D debris increase with only moderate population projection. As one of the fastest growing cities in the U.S., Seattle's population has the potential of increasing at a much faster rate, which may lead to higher waste generation. An rapid increasing of waste generation may cause existing landfills in Washington to reach full capacity earlier than projected. Thus, it is crucial for Washington to explore more efficient waste treatment options for the purpose of reducing waste generation. Waste reduction may be accomplished in several ways, including increasing waste diversion rate, use of recyclable materials, and promoting recycling/reuse through public programs and policies, etc.

Waste reduction needs to take place in response to the increasing population. Increasing the adoption rate of wood materials such as CLT in the construction industry will reduce the amount of waste generated from construction and demolition. By replacing concrete and steel building components with CLT components that serve the same purpose, a significant amount of building-related wastes will be reduced over time. Combining CLT with concrete and steel in new building construction can eventually lead to significant reduction in C&D waste. In addition to material substitution with CLT, other features of using CLT, such as faster construction times and lighter weight, may also lead to impact reduction. Faster construction time can limit the amount of on-site waste generation, and lighter weight makes wood materials easier to handle during collection and transportation, and thus, reduces emissions from transportation. Another potential benefit of waste reduction is that the number of years for existing landfills to reach full capacity is extended, meaning that the negative impacts associated with establishing more landfill sites are reduced.

3.10.2. Emissions from CLT Disposal

The level of methane emission from waste disposal depends on several factors, including waste composition, landfill condition, the rate of chemical reaction, and LFG control practices, etc. For wood products like CLT panels, biogenic carbon dioxide emissions, a two way flow to and from the atmosphere are considered carbon neutral. Methane contribution from CLT varies depending on moisture conditions and LFG control. Total methane emission is lower under dry conditions compared to wetter conditions, thus, if no LFG collection practice takes place, considering disposal in wetter landfill conditions may help reduce total methane generation over time, assuming the reaction rate within the landfills is constant. However, if methane recovery is adopted for energy purposes, it may be beneficial to increase the amount of methane collected as it would increase energy production. Several major MSW landfills in Washington have already installed LFG collection systems and adopted energy conversion practices. Based on the results of this study, disposing of CLT panels that are not recycled or reused in landfills in eastern Washington may appear as a better option since methane recovery potential is higher due to eastern Washington's drier condition. However, additional input such as transportation and costs for fuel and labor need to be considered before deciding the best treatment option for CLT.

Adhesives used in wood products could be an emission contributor as they are an unavoidable component. Unlike wood, carbon emission from adhesives is not biogenic, meaning it will post positive net carbon emission and contributes to climate change. Many efforts are being made to develop bio-based adhesives and adhesives containing lower formaldehyde (Ferdosian et al. 2017; He 2017; Kim 2009; Wool and Sun 2011), but formaldehyde-based adhesives such as MF are still commonly used in wood products. Puettmann et al. (2018) considered melamine-based adhesive in CLT panel, whereas our study uses PUR adhesive. Using PUR instead of MUF can significantly reduce the amount of formaldehyde emission. Using bio-based adhesives can reduce toxic emissions from CLT, but the economic feasibility of using such adhesives for CLT manufacturing requires further research. Adhesives emissions from incineration is usually considered low impact to human health, but this assumption requires further investigation (Messmer 2015).

This chapter has shown that using CLT in construction projects can be beneficial in terms of waste reduction and reducing fossil CO_2. For the same structural purpose, buildings that use CLT to partially replace concrete require less material because CLT is lighter in mass, which in turn, can reduce the amount of C&D waste generated in the future. Existing literatures concluded that wood generates higher methane emission per unit of material in landfills compared to concrete (Sathre and O'Connor 2010b; Upton et al. 2008). One main cause of this phenomenon is the fact that wood decomposes much faster than concrete. However, methane emissions can be significantly reduced if CLT is not landfilled (Börjesson and Gustavsson 2000).

While producing aggregate from recycled concrete generates significant levels of carbon (Bravo et al. 2015), the recycling and reuse of CLT is more efficient for many reasons. For instance, wood products may be used for energy to offset emissions produced by burning fossil fuel.

This study estimates the emissions of CLT under a baseline scenario which assumes the materials are disposed of in landfills at the EoL stage. In practice, recycling and reusing wood products are usually encouraged, and in some regions, are required. Based on the data released by DOE, among all C&D debris generated, the diversion rate of wood materials ranged from 15% to 22% between 2003 and 2013. As a wood product, CLT can be recycled and reused. By recycling CLT panels, emissions from landfills are reduced through waste reduction. Recycling and reusing CLT can also contribute to energy conservation since wood products can often be used to generate electricity. The environmental impacts of recycling as compared to landfilling or energy recovery are investigated in the next chapter.

3.11. Conclusion

Emissions from CLT panel disposal strongly depend on the treatment options. The location and condition of landfills, waste-to-energy facilities, and recycling facilities can contribute significantly to environmental impacts posted by CLT panels. However, location of facilities is not the only factor that determines the impacts of CLT disposal. When deciding on the EoL treatment of CLT, it is important to consider the entire cycle of the EoL phase since any activities associated with EoL can contribute to the total environmental impact of CLT. Activities involved in the EoL phase may include separation of demolition debris, transportation of CLT to treatment facilities (i.e. landfills, transfer stations, recycling facility, waste-to-energy facility, etc.), and final disposal. To evaluate different EoL treatment options for CLT, several case scenarios are modeled in the next chapter using a life cycle assessment (LCA) approach.

Chapter 4: Evaluating the Environmental Impacts of CLT at the End-of-Life Phase using Life Cycle Assessment

This chapter develops and investigates the environmental impacts of an end-of-life (EoL) scenario of CLT. The scenario is developed based on existing data and practice associated with waste management in Washington. This study provides regional-specific model of the potential impacts of CLT disposal and compares with the results in Chapter 3.

4.1. Background

The EoL options for a product usually fall into one of the following categories: landfilling, recycling, reuse, or incineration. Wood waste treatments usually involve waste transfer stations, material recovery facilities (MFRs), and final disposal sites such as landfills and incineration facilities (Schneider 2013). Transfer stations serve as a facility for waste unload and diversion. The main purpose of transfer stations is to provide an opportunity for waste separation and sorting before they are disposed in landfills. Transfer stations also provide convenient drop-off points for the public without the use of large vehicles for waste transportation. MFR are facilities that divert and process recyclable materials. MFR may include transfer stations in some regions. In Washington, transfer stations often provide recycling services. For example, King County has several transfer stations that distribute recyclable wastes to domestic and international markets for reprocessing into new products. Non-recyclable materials are often transported to landfills or waste-to-energy facility.

Clean wood materials from C&D debris may often be considered for recycling or reuse before they are disposed in landfills. As a type of engineered wood product, CLT is an appropriate alternative construction material over concrete and has many benefits. Wood often has recycling and reuse value and may be made into various products for secondary uses after appropriate treatment. Treatment options for CLT panels after demolition may include landfill disposal, recycling, incineration, or resale. The recycling of wood is often encouraged. Like many wood products, untreated wood from C&D can be resold in the market or processed into secondary products. Chipped wood may also be used for paper manufacturing or mulch. Nonetheless, the actual recycling options for wood from C&D debris are limited. Schneider

(2013) suggested that the most common usages of recycled wood from C&D debris is energy recovery or hog fuel. A waste-to-energy facility is available in eastern Washington and may be used as a potential EoL option for CLT.

According to DOE's data, wood waste accounts for approximately 20% of all C&D related materials from 2003 to 2013. Based on the average diversion rate for C&D materials, approximately 57% of the wood wastes are diverted and the rest are disposed in landfills. Among diverted wood wastes, 40% are recycled and 60% are used for energy recovery. Although the wood diversion rate dropped slightly after reaching a peak in 2010, the rate of C&D related wood diversion shows an overall increasing trend from 2003 to 2013. Counties and cities are attempting to increase the recycling and reuse rates of C&D debris. For instance, Seattle has a goal of reaching 70% recycling rate for C&D materials by 2020, especially increasing the rate of beneficial uses of wood materials (Seattle Public Utilities [SPU] 2018). Because of the many efforts to increase recycling rates, it is likely that the wood recycling rate will increase.

Treatment options for CLT panels after demolition depend on many factors, including facility availability, local and regional regulation, economic feasibility, public cooperation, and geographical location. From an environmental perspective, any activities involved during the EoL phase can contribute to the final impact from CLT treatment. The impacts of these options require detailed modeling to ensure the important processes and factors involved are taken into account.

Life Cycle Assessment (LCA) is a tool for modeling the impacts of a product or service throughout the life cycle stages. Details associated with LCA methodology are described in

Chapter 1. LCA has been applied in various studies associated with wood products and wood buildings because of its ability to provide a clear overview of the impacts related to the production system. Many studies have already applied LCA modeling to research associated with CLT and provided references for this study, and the EoL impacts of mass timber have been described (Darby et al. 2013; Dodoo et al. 2009; Durlinger et al. 2013; Peñaloza et al. 2016; Takano et al. 2015). Nonetheless, most of these existing studies do not apply to North America as the parameters they use are based on European standards. This chapter uses LCA to model the impacts of treating CLT panels after a building's service life and establishes an EoL case scenario based on current data and technology, specifically for Washington.

4.2. Methodology

This study emphasizes the environmental impacts of CLT panels at the end-of-life stage. Different treatment scenarios for CLT after demolition are evaluated based on current technology and available facilities. The total impact of CLT from these treatment scenarios are modeled and compared using a life cycle assessment (LCA) approach. Details associated with the LCA methodology framework are described in Chapter 1.

4.2.1. End-of-Life System Scenario

The EoL scenario modeled in this chapter is developed based on the current waste diversion data in Washington. Many regions in Washington, for instance, Seattle, suggest that untreated wood materials should be recycled or reused instead of landfilling whenever possible, which makes 100% landfilling of wood wastes unlikely. It is common for a type of waste to go through multiple treatments at the EoL phase. To make the EoL model realistic and practical, a case scenario that includes multiple waste treatment options is modeled.

The EoL system may show significant variations depending on the location of wastes, technology availability, legislation, and operating costs. This chapter develops a case scenario based on currently available facilities and technology and includes several common waste treatment options. In this scenario, a proportion of CLT materials are diverted at a transfer station for reuse or incinerated for energy recovery while the remaining materials are transported to a final disposal site. The current rate of wood recycling among diverted wood materials is 40%, however, it is expected that the recycling rate is likely to increase in the future, so a 60% recycling/reuse rate is used in this case scenario.

In the scenario modeled here, at the transfer station, a portion of CLT (~60%) is diverted. Around 60% of the diverted CLT, or 36% of the total CLT material, is reused or recycled into secondary materials, and the other 40% of diverted wood, or 24% of the total CLT material, is burned for energy. C&D materials are transported to the transfer stations using light commercial trucks. The materials are shipped to the next facility or disposal site using long-haul vehicles such as combination trucks. The waste transfer stations are located within or near King County since the construction site is located in Seattle. A proportion of diverted CLT materials are burned in an incineration facility and the remaining materials are distributed to reclaimed wood products market for resale around Seattle. Materials not reused or burned are transported to a final disposal site. The final disposal site is a landfill in Cowlitz County.

4.2.2. LCA Method

LCA is used to determine the environmental impacts associated with different stages throughout the life cycle of CLT panels. This chapter focuses on the EoL phase and estimates the impacts from CLT panels based on typical waste treatment options available in Washington. The scope of this study is to model the environmental impacts of CLT treatment options at the end-of-life stage. The functional unit is 1 m^3 of CLT panel, with a bone dry density of 472 kg/m^3, including the wood and resin components.

4.2.3. System Boundary

Figure 4.1 describes the system boundary of this study. The system begins at the demolition site where CLT panels are separated from the building and become demolition waste. The CLT materials are then transported to nearby transfer stations for sorting and diversion. A proportion of the panels are diverted for recycle or energy recovery while the rest of the materials are transported to the final disposal sites. Transportation of the wastes is included in the system. Input includes fuels, electricity, and energy used during transportation and treatments of the CLT materials.

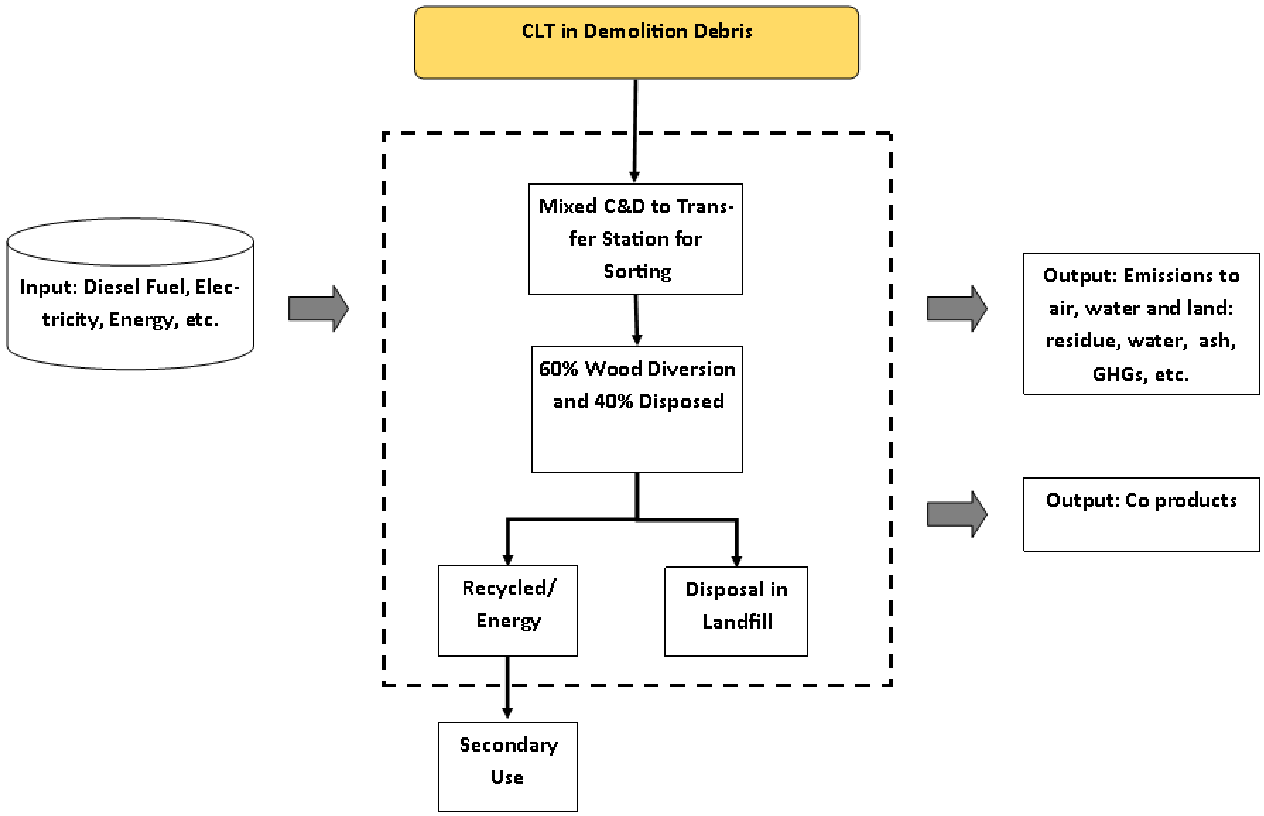


Figure 4.1. System boundary. The system described in this study begins at the construction site, after the building is demolished, and ends at the final disposal/treatment stage.

4.2.4. Impact Assessment

SimaPro and the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI 2) are used to model the environmental impacts resulting from the processing and transportation systems described previously. SimaPro is a software tool for modeling production and processing systems from a life-cycle perspective based on the system flow developed by the user. SimaPro integrates a number of worldwide databases for impact analysis and users may select the processes that are the most appropriate. TRACI 2 is a midpoint impact analysis method developed by the U.S. Environmental Protection Agency. This method uses input parameters that are consistent with U.S. geographic locations and currently provides normalization data for both the U.S. and Canada. Global warming potential (GWP), acidification, eutrophication, ozone depletion, and smog are some of the main impact categories included in TRACI 2 and will be evaluated in this chapter.

4.2.5. Input Data and Assumptions

SimaPro requires the users to input the necessary parameters associated with the EoL process. The parameters are calculated based on the raw data, which can be either primary or secondary data. Input data used in this chapter was collected from various sources, including existing literature, personal correspondence, online data, official records and documentation. Fuel and energy consumption that occur during the EoL treatment of CLT panels are taken into account based on the distribution of the wastes. The Washington's Department of Ecology (DOE) provided the basis for the waste treatment scenario developed in this chapter (G. Newman, personal communication, February 15, 2018). Information associated with treatment facilities and disposal sites was obtained from various state and county online databases. Input data associated with the transportation logistics was modeled using the network analysis tool in ArcGIS. The USLCI and Ecoinvent databases provided inventory data for some of the processes involved in the EoL phase, including electricity and fuel production and resin production, as well as incineration and landfill data for polyurethane and wood.

The transportation logistics are modeled based on the location of the facilities. The energy consumption for transporting the CLT materials depends on the time traveled between facilities and the amount of material transported. The traveling time is closely associated with distance, road restrictions, and road conditions. ArcGIS was used for modeling the transportation distance and condition between facilities. Road restrictions were taken into account and only roads that are accessible by larger trucks were considered. Ferries and other water transportation modes were strictly avoided during transportation under this scenario. Facilities (except the hypothetical building site) included in this study are all operating facilities in Washington State. Table 4.1 shows the input data based on GIS analysis and case scenario assumptions.

Table 4.1. Units and measures associated with EoL. Transportation distances and the amount of materials for each treatment option are described.

	Unit	**Amount**
From Construction Site		
Building Site to Transfer Station	km	26
CLT	m^3	1
	odkg	472
Landfill		
Transfer Station to Landfill	km	178
CLT	m^3	0.4
Incineration		
Transfer Station to WTE Facility	km	451
CLT	m^3	0.24
Reuse		
To Nearby City	km	26
CLT	m^3	0.36

4.2.6. Assumptions

1. The CLT panels consist of two main wood species: Douglas-fir and Western Hemlock, giving the material a bone-dry mass of ~472 kg/m^3.

2. The reuse option assumes the materials are distributed into the market for secondary use and the impacts of secondary uses are not included in the system described in this study.
3. The loading time of the CLT materials are not included in the transportation process.

4.3. Results

Based on the EoL system description produced in previous sections, the CLT panels are allocated to different treatment options, including landfill, incineration, and reuse. Although different amounts of CLT are distributed to different treatment processes, the final impacts of a total volume of 1 m^3 of CLT (the functional unit) are presented at the end of this section.

4.3.1. Impact Categories

Several impact categories are evaluated in this chapter, including GWP (CO_2 equivalent), acidification potential (SO_2 equivalent), eutrophication (N equivalent), and smog potential (O_3 equivalent). GWP is a key characterization factor for assessing the impact on a global scale, while acidification and eutrophication potentials evaluate the impacts on the regional and local scale. Smog potential is also analyzed since it may be related to human health issues and vegetation damages at the regional and local level (Curran 2006). In addition, impacts of carcinogenic and non-carcinogenic effects, respiratory effects, and eco toxicity are also described in this section. The EPA recommended unit used for carcinogenic and non-carcinogenic effects is CTUh (comparative toxic unit for human toxicity potential), while the recommended unit for eco toxicity is CTUe (comparative toxic unit for ecotoxicity potential). Respiratory effects uses PM2.5 eq.

4.3.2. Landfill

Landfilling is one of the most common waste treatment methods. Table 4.2 shows the amount of impacts for each main life cycle impacts category of 0.4 m^3 of CLT. Since each CLT panel is consisted of wood and adhesive, impacts from both wood and resin are presented. In addition, the EoL process includes the transportation of the wastes to the transfer station and to the landfill. The total GWP contributed by landfilling 40% of the CLT materials is approximately 26 kg CO_2 eq. for every m^3, meaning that the substances released from this process have the same global warming potential as 26 kg of CO_2. The transportation of CLT materials contributes 14.46 kg CO_2 eq. to the total GWP and the landfilling of the wood portion contributes 11.89 kg CO_2 eq. Assuming the CO_2 from wood is biogenic, the result of the LCA model indicates that methane is the main contributor to the relatively higher GWP of the wood.

Table 4.2. Environmental impacts of disposing of CLT in landfill, assuming 40% of 1 m^3 of CLT are disposed.

Impact Category	Unit	Transportation	PUR Resin	Wood Portion	Total
Global Warming	kg CO_2 eq.	14.46	0.25	11.89	26.6
Acidification	kg SO_2 eq.	0.092	0.00036	0.016	0.11
Eutrophication	kg N eq.	0.0052	0.083	1.35	1.44
Smog	kg O_3 eq.	2.51	0.067	0.36	2.94
Ozone Depletion	kg CFC-11 eq.	6.05E-10	1.05E-08	6.78E-07	6.89E-07
Carcinogenic	CTUh	2.16E-07	1.24E-08	1.53E-07	3.81E-07
Non-carcinogenic	CTUh	2.09E-06	2.07E-06	7.44E-06	1.16E-05
Respiratory Effects	kg PM2.5 eq.	0.0058	0.000074	0.0027	0.0086
Ecotoxicity	CTUe	40.02	125.26	164.59	330

Assuming landfill is the final disposal site for 40% of the CLT (0.4 m^3), Figure 4.2 illustrates the contribution of each component within the process. Transportation appears to be the largest contributor in several impact categories, including global, warming, smog, acidification, carcinogenic effects, and repiratory effects. However, there is almost no contribution from transportation in the categories for ozone depletion and etrophication. The landfilling of wood contributes the most to ozone depletion, etrophication, and non-carcinogenic effects. Impacts from the landfilling of wood account for a relativly high proportion in almost all categories, except for smog and acidification. Contributions from the resin are relatively low compared to the transportation and the landfilling of the wood portion. In the non-carinogenic effect and the eco toxicity categories, resin accounts for a relatively higher portion of contribution within the entire landfilling process.

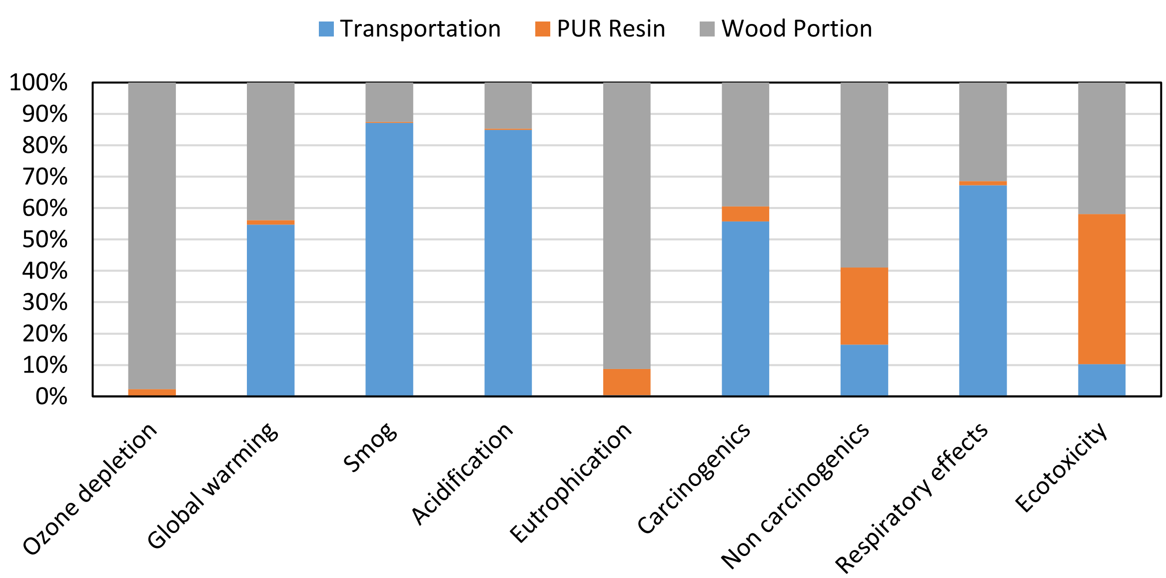


Figure 4.2. Contribution of each stage to the landfilling of 0.4 m^3 of CLT.

4.3.3. Incineration/WTE

Incineration is another waste treatment process included in this study. Based on the EoL system scenario for this study, 60% of the total waste is diverted. Of this, 40% of the diverted CLT panels, or 24% of the total, are incinerated for energy at a waste-to-energy (WTE) facility. Table 4.3 shows the impacts from incineration. The transportation phase includes the transport of CLT panels to the transfer station and to the WTE facility. Impacts from both the resin and the wood portion are assessed separately. The total GWP from the incineration process is 21.4 kg CO_2 eq. Transportation accounts for 15.59 kg CO_2 eq., which is higher compared to the GWP contributed by the incineration of resin and wood. With 1.58 kg CO_2 eq., the incineration of the wood portion of CLT has the lowest GWP.

Figure 4.3 shows the contribution of each component in the incineration process. The resin portion of CLT contributes more in the eco toxicity category, while the wood portion contributes a higher amount in ozone depletion, eutrophication potential and non-carcinogenic effects. The transportation of materials has higher impacts in GWP, smog and acidification potential, and respiratory effects, but has almost no impacts in the ozone depletion category. Overall, both transportation and resins appeared to have higher GWP in this process compared to the wood. Similar to the landfill option, PUR resin accounts for a large proportion of the eco toxicity impact.

Table 4.3. Environmental impacts of incineration, assuming 0.24 m^3 of CLT goes to incineration.

Impact Category	Unit	Transportation	PUR Resin	Wood Portion	Total
Global Warming	kg CO_2 eq.	15.59	4.2	1.58	21.37
Acidification	kg SO_2 eq.	0.104	0.004	0.018	0.13
Eutrophication	kg N eq.	0.0059	0.002	0.036	0.044
Smog	kg O_3 eq.	2.85	0.11	0.53	3.49
Ozone Depletion	kg CFC-11 eq.	6.52E-10	2.1E-08	1.34E-07	1.56E-07
Carcinogenic	CTUh	2.33E-07	9.38E-08	3.07E-07	6.34E-07
Non-carcinogenic	CTUh	2.25E-06	6.14E-07	3.4E-06	6.26E-06
Respiratory Effects	kg PM2.5 eq.	0.006	0.00011	0.0015	0.0076
Ecotoxicity	CTUe	43.48	74.32	58.56	176

If 24% of the waste CLT is incinerated for energy, the carbon content would equal to 205 kg CO_2. With 70% efficiency to displace Natural Gas in a typical mill boiler, 144 kg CO_2 is available to displace most of the 156 kg CO_2 for producing both the Lumber and CLT, not including transportation (Table 2.7). Energy recapture from CLT waste may not be as good as reuse but is a very important alternative, and a major improvement over incineration without energy recovery.

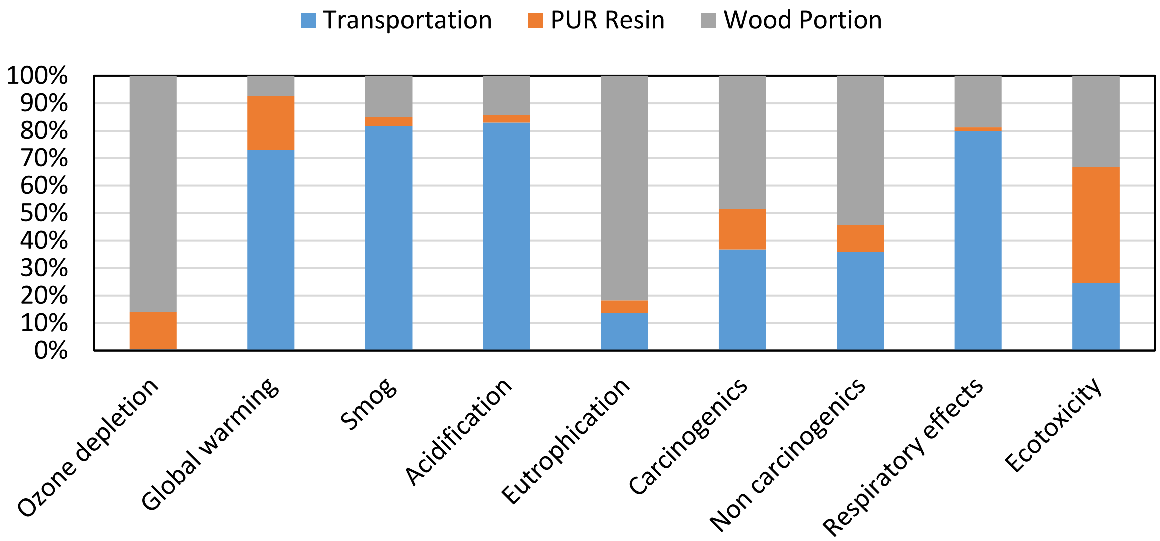


Figure 4.3. Contribution of each stage to the landfilling of 0.24 m^3 of CLT.

4.3.4. Reuse

Assuming 60% of the diverted CLT materials are reused and/or resold, they may be transported to nearby cities for secondary uses. Since the environmental impacts of secondary uses are beyond the system boundary of this study, only the environmental impacts caused by transportation of the used CLT panels are included in this analysis. Table 4.4 presents the impacts of hauling the waste CLT to the transfer station and hauling a proportion of the diverted materials back to Seattle for reuse/resale. The total GWP is 14.52 kg CO_2 eq. if a proportion of the CLT panels are distributed to nearby urban regions for secondary use. The CLT materials are assumed to remain laminated and therefore the resin portion is not separated from the wood portion.

Table 4.4. Environmental impacts of reusing CLT, assuming 0.36 m^3 of CLT is reused.

Impact Category	Unit	Total
Global Warming	kg CO_2 eq.	14.52
Acidification	kg SO_2 eq.	0.092
Eutrophication	kg N eq.	0.0052
Smog	kg O_3 eq.	2.49
Ozone Depletion	kg CFC-11 eq.	6.07E-10
Carcinogenic	CTUh	2.17E-7
Non-carcinogenic	CTUh	2.09E-6
Respiratory Effects	kg PM2.5 eq.	0.006
Ecotoxicity	CTUe	40.48

4.3.5. Total Impacts from EoL

The EoL system scenario in this study presents three different options (i.e. landfill, incineration, and reuse) for waste associated with CLT panels. Figure 4.4 shows the impacts for each of these three options and the degree of contribution each option. The landfill option is the largest contributor to ozone depletion and eutrophication. However, the landfilling of CLT indicates relatively lower environmental impacts compared to incineration in smog potential, acidification potential and carcinogenic effects. Incineration at the WTE facility posts higher impacts in the carcinogenic category and posts low impacts in eutrophication compared to landfill disposal. The reuse option appears to post very low impacts to ozone depletion and eutrophication while it contributes higher impacts to categories such as smog, acidification, and respiratory effects, which is primarily attributed to the transportation of the reused CLT panels.

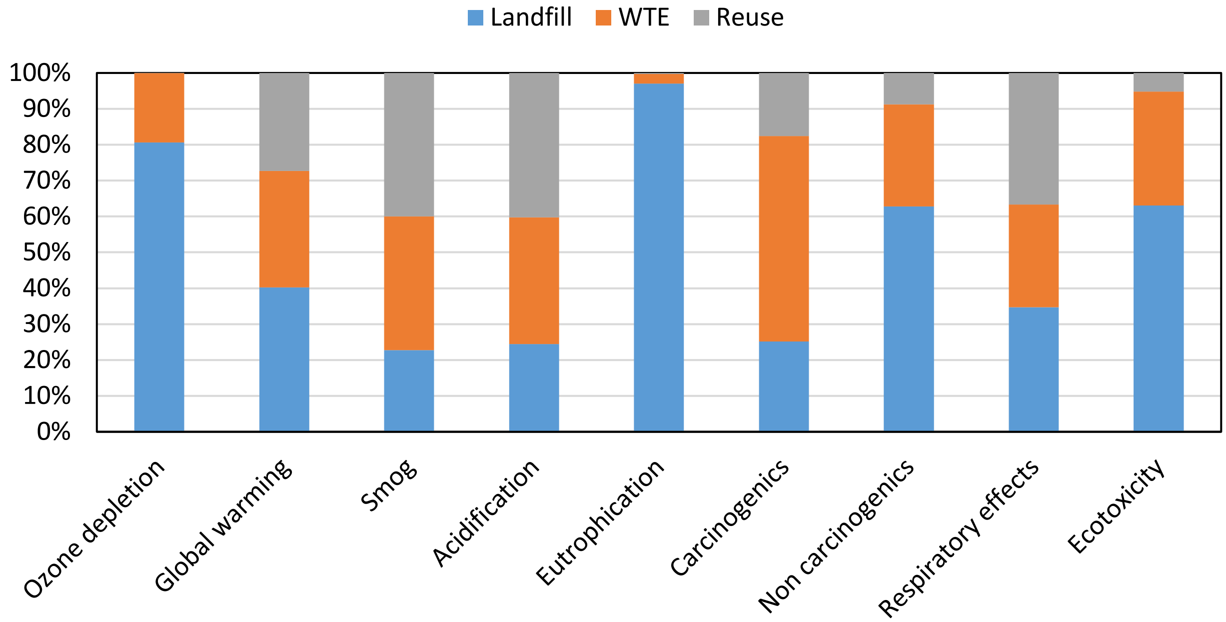


Figure 4.4. Contribution of each EoL option to the total environmental impact of treating 1 m^3 of CLT. Among 1 m^3 of CLT, 40% are landfilled, 24% are incinerated, and 36% are reused.

Compared to using only one waste treatment option, combining recycle/reuse along with landfill and incineration can limit the negative environmental impacts. As shown in Table 4.5, assuming that the 1 m^3 of CLT material goes to either landfill or incineration only, the GWP for both of these options are higher than the scenario proposed in this study (i.e. the combined scenario). For smog potential, although the combined treatment scenario has higher impact than landfill and reuse only, it reduced the smog potential by 41% compared to incineration alone. Reusing 100% of the CLT panels would produce the lowest environmental impacts.

Table 4.5. Impacts of treating 1 m^3 of CLT under each waste treatment option, as compared to the scenario described in this chapter.

Impact Category	Unit	Landfill Only	Incineration Only	Reuse Only	Combined Scenario (40% Landfill, 24% Incineration, 36% Reuse)
Global Warming	kg CO_2 eq.	49.57	55.23	21.35	42.83
Acidification	kKg SO_2 eq.	0.17	0.31	0.14	0.19
Eutrophication	kg N eq.	3.68	0.17	0.01	1.48
Smog	kg O_3 eq.	4.44	8.74	3.67	5.24
Ozone Depletion	kg CFC-11 eq.	1.73E-06	6.48E-07	8.92E-10	8.55E-07
Carcinogenic	CTUh	7.32E-07	2.14E-06	3.19E-07	9.59E-07
Non-carcinogenic	CTUh	2.93E-05	2.12E-05	3.08E-06	1.72E-05
Respiratory Effects	kg PM2.5 eq.	0.01	0.02	0.01	0.014
Ecotoxicity	CTUe	937.42	640.55	59.55	523.37

It is important to note that, under the reuse scenario considered in this research, it is assumed that the carbon stored in the CLT wood remains in the product. The carbon content in wood accounts for half of the mass of the wood (Sathre and O'Connor 2010a). Given that the wood portion of the CLT is assumed to be 466 kg/m^3 in this research, the carbon content stored in CLT is 233 kg/m^3. Based on the carbon content, we can calculate the amount of CO_2 in the CLT to be approximately 854 kg per m^3 of CLT. If this amount of CO2 is accounted for under the reuse scenario, the environmental impact of reuse would become negative.

4.3.6. Emission Contribution of Materials in Landfill Disposal and Incineration

If the expected CLT demand is met by 2035, a total of 54,416 m^3 of CLT may be used for office buildings in Seattle. Assuming the average service life of a building is 75 years, these CLT panels will become a part of the demolition debris and require proper EoL treatment by 2110. Using results calculated in Chapters 3 and 4, the environmental impact contributions of landfilling the materials included in the slabs with CLT replacement are shown in Figure 4.5. The GWB in the CLT slab contribute significantly to the acidification potential and respiratory effects, while CLT contribute the most to GWP and eutrophication. Concrete has a slightly higher contribution of smog compared to CLT and gypsum wallboard (GWB). It is important to note that, Figure 4.5 does not account for the carbon stored in the CLT over its service life or the fossil fuels replaced by wood, and only shows the emissions of the materials. As it may appear that CLT has a relatively high contribution to GWP. However, accounting for the carbon content in the product or fossil fuel substitution, the carbon stored would potentially offset and outweigh the emissions. More details are described in Chapter 5.

The major contributors from GWB to acidification are sulfur dioxide (SO_2), nitrogen oxides (NO_x), and hydrogen fluoride (HF), based on the inventory analysis in SimoPro. As shown in Table 4.6, among slabs with CLT replacement that are assumed to be disposed of in 2110, GWB contributes 561,468 kg of SO_2, which is also the most significant contributor from GWB to the acidification potential. The SO_2 contribution of CLT and concrete is 773 kg and 1140 kg, respectively, significantly lower than that of GWB. The high contribution to the respiratory effects from GWB is mainly caused by SO_2 and particulate matters.

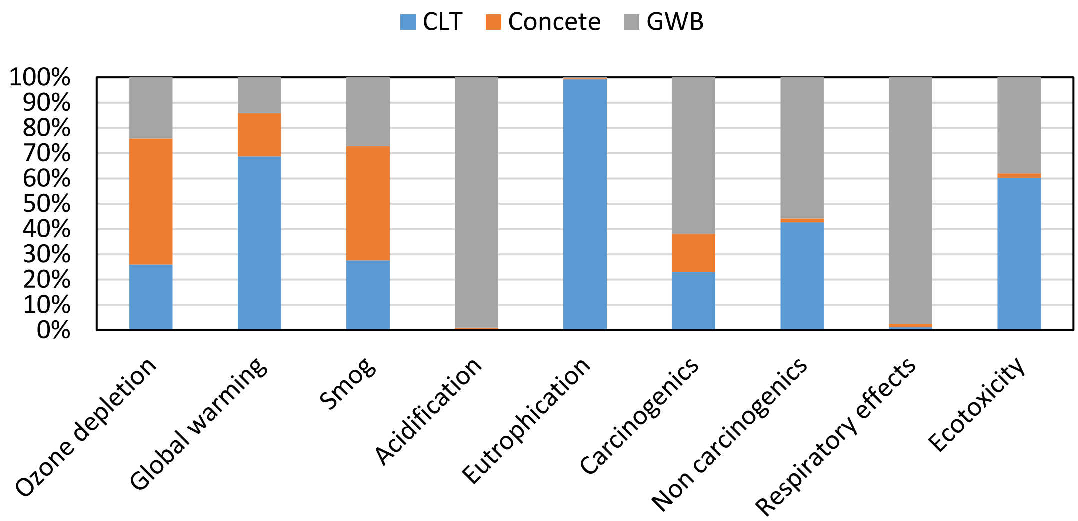


Figure 4.5. Impact contribution of each material in slabs with CLT replacement in landfills.

Because of the higher contribution of methane and SO_2 in CLT slabs in landfills, it is important to reduce the amount of disposal. Supposing available CLT over the next 30 years is enough for use in concrete/CLT mixed building slabs for a certain number of new buildings, the amount of concrete required in these building slabs would be reduced as compared to the case where no CLT is used in these buildings. Another option for CLT is energy generation through incineration. Figure 4.6 shows the contribution of each material contained in a CLT system slab. Compared to the landfill option, impacts such as global warming and eutrophication associated with CLT disposal are slightly reduced. However, CLT's contribution to impacts such as smog and carcinogenic effects increased.

Table 4.6. Emissions from each material in CLT slabs that are expected to be disposed in landfills by 2110.

Emission Contribution of Materials in Slabs with CLT	GWB (kg)	CLT (kg)	Concrete (kg)	Total (kg)
Global Warming				
Methane	795	58,820	732	60,347
Acidification				
Sulfur Dioxide (SO2)	561,468	773	1,140	563,381
Nitrogen Oxides (NOx)	2,004	2,022	3,321	7,347
Hydrogen Fluoride	4,601	773	1.46	5,375
Respiratory Effect				
Sulfur Dioxide (SO2)	561,468	773	1,140	563,381
Particulate Matter (<2.5 µm)	357	301	379	1,037
Particulate Matter (>2.5 µm and <10µm)	87	72	77	236
Eutrophication				
Ammonium	10	19,310	1.19	19,321
BOD5, Biological Oxygen Demand	3,807	683,853	2,332	689,992
COD, Chemical Oxygen Demand	4,632	2,892,362	2,448	2,899,442
Smog				
Nitrogen Oxides	2,004	2,022	3,321	7,347

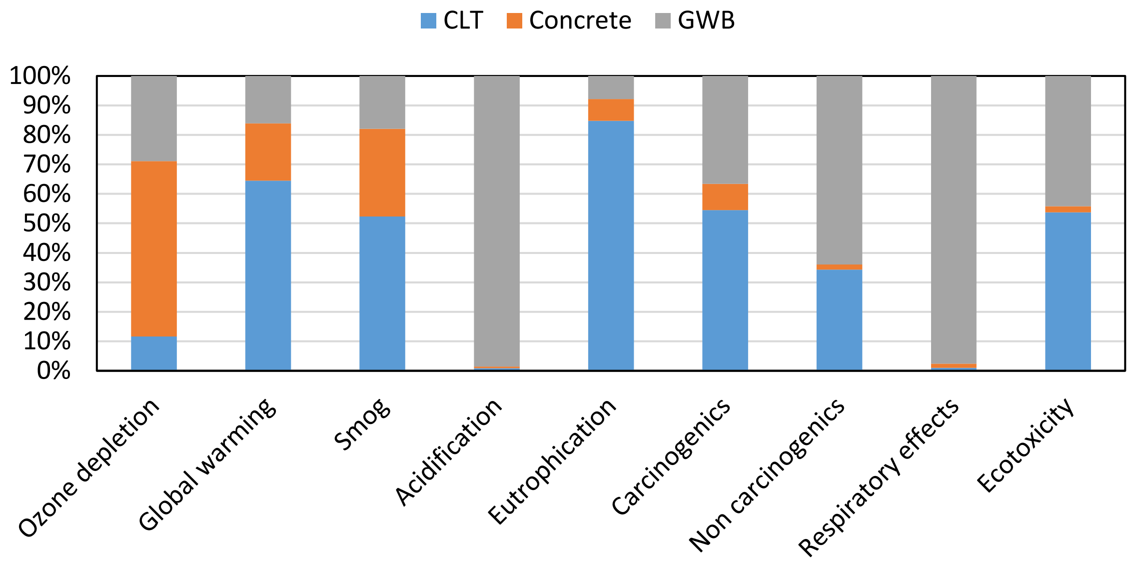
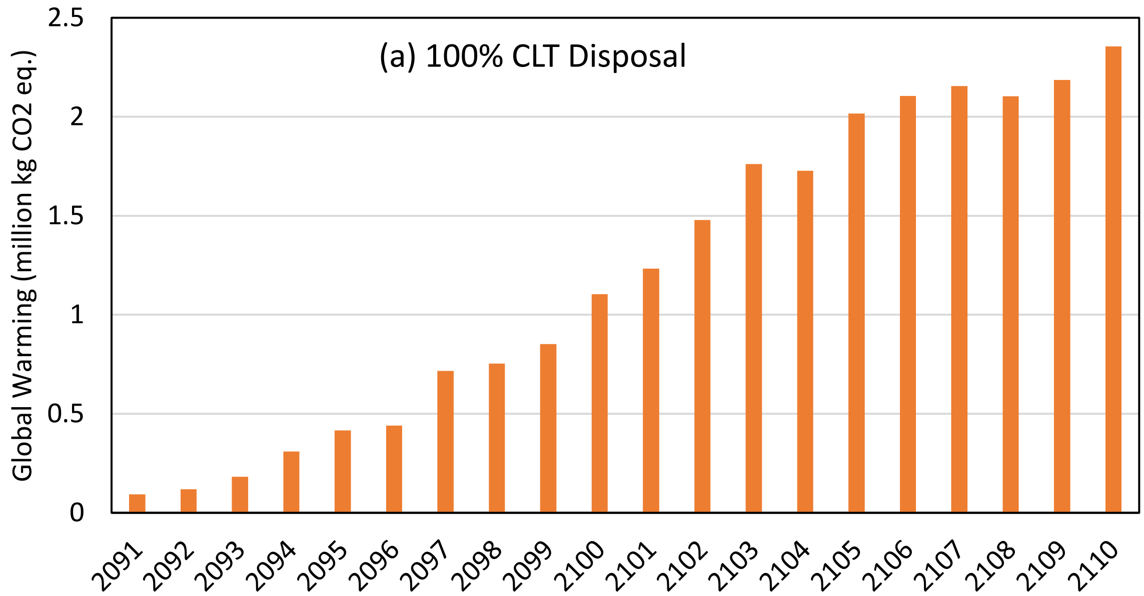


Figure 4.6. Impact contribution of each material in slabs with CLT replacement if incinerated.

When CLT reuse is taken into consideration, the total impacts of using CLT and concrete only can vary depending on the rate of CLT reuse. Figure 4.7 shows the GWP of different CLT disposal scenarios based on the estimated amount of CLT disposed of in that year: the GWP is reduced as the amount of CLT landfill disposal is reduced and the rate of reuse is increased. Four CLT treatment scenarios are considered: (a) 100% of the CLT materials are disposed in landfill, (b) baseline scenario described in Chapter 4, where 40% of the CLT are landfilled, and 24% are incinerated, and the rest are reused, and (c) 10% of the CLT materials are landfilled, 20% are incinerated, and the remaining 70% CLT materials are reused. Scenario (c) is based on the 2020 C&D recycling goal in Seattle. Out of the four scenarios, scenario (c) demonstrates lower GWP compared to scenarios (a) and (b). All GWB and concrete were assumed to be landfilled under these scenarios. It is considered not practical to reuse 100% of the CLT materials, and thus, achieving a higher reuse rate is a more feasible option than attempting to reuse all CLT material. As shown in Figure 4.7, as the rate of reuse increases, the global warming impact decreases. The impacts shown here are only based on the emissions associated with the EoL phase and do not account for the carbon content remaining in the CLT.



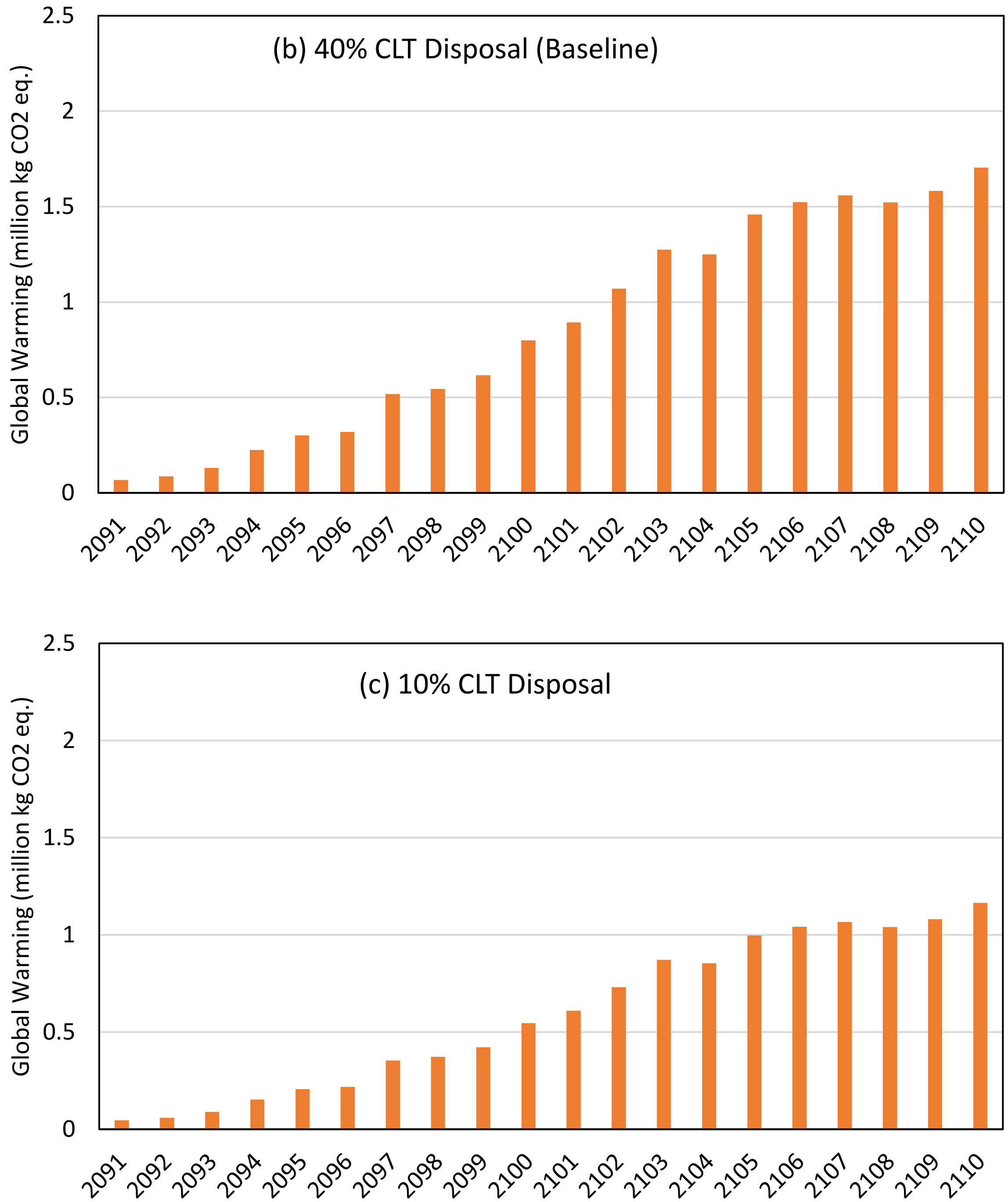


Figure 4.7. Global warming potential comparison of building slabs with CLT substitution under different EoL scenarios. Materials considered include CLT, GWB, and concrete.

4.4. Discussion

The impacts of the EoL phase are closely associated with the amount of materials allocated to each treatment option. The landfilling of wastes usually leads to higher eutrophication potential due to leachates that are harmful to aquatic systems. On the other hand, incineration at the WTE facility has higher carcinogenic impacts due to the burning of waste, particularly hazardous materials such as the polyurethane resin (PUR). Under the case scenario described in this study, landfill contributes a relatively higher impact to global warming. This is due to the fact that a larger amount of materials are sent to landfills: 0.4 m^3 to landfill compared to 0.24 m^3 to incineration and 0.36 m^3 to reuse.

Like many engineered wood products, CLT requires a certain amount of adhesives to bind the lumber layers together. Since CLT can be used as structural components, over 6 kg of PUR adhesives are used for every cubic meter of CLT to maintain a strong bonding. PUR-based adhesive is used in this study and the landfilling and burning of polyurethane may have contributed higher impacts to ecotoxicity since it accounts for higher proportion of the environmental impacts compared to wood and transportation. In both the landfill and incineration options, PUR showed significant increase in environmental impact contributions in ecotoxicity over other impacts categories. The amount of ecotoxicity impact from PUR is 74.32 CTUe for incineration and over 125 CTUe for landfill.

The transportation of materials contributes mainly to global warming, acidification, and smog. This may be due to the consumption of diesel fuel in commercial trucks, and the total impacts from transportation are closely associated with the traveling time and distance. The transportation phase has a higher global warming impact in the incineration process, even though the amount of materials transported to the WTE facility is only 40% of all diverted materials. This is because the WTE facility is located further away from the building site and from the transfer station and requires longer truck traveling times compared to the other options. Although the GWP from the landfilling of CLT materials is higher than that of incineration (12 kg CO_2 eq. compared to 5.8 kg CO_2 eq.), the incineration process holds the highest transportation GWP among all three options.

Wood products can become a source of methane, a key greenhouse gas, during degradation. As described in Chapter 3, depending on the landfill moisture conditions and landfill gas (LFG) treatment, the methane released from one dry kg of wood can range from 0.0023 to 0.0093 kg over 100 years. The landfill option described in this chapter includes energy recovery from LFG and the total methane released over a 100-year time frame is 0.43 kg for 0.4 m^3 of CLT (40% of the functional unit), meaning approximately 1.1 kg of methane is released for every 1 m^3 of CLT. Based on the results from Chapter 3, under moderate landfill condition and with energy recovery from LFG, approximately 1.3 kg of methane is produced for every 1 m^3 of CLT, which validates the results from the LCA modeling in this chapter. If the landfill conditions are drier, total methane generation would be higher than the results from this LCA model, and when landfill condition is wetter, methane generation would be lower compared to the results from the LCA model. The inventory data for LCA was modified and generalized for the U.S. average, thus, the results from the two studies may be different. Nonetheless, the results from Chapter 3 and Chapter 4 indicated that the location of the landfill and amount of material disposed are important factors in reducing the environmental burden from CLT.

Incineration of CLT for energy recovery can offset the carbon produced from fossil fuel burning. However, establishment of energy recovery facilities requires careful planning because the transportation of materials can significantly influence on the level of environmental impacts. For instance, transporting CLT waste generated in Seattle to a WTE facility in eastern Washington is not efficient from an environmental perspective. Since CLT is more likely to be used in tall buildings in the city, establishing a WTE facilities near populated cities can reduce impacts from transportation. However, this may not be a practical option since incineration can yield higher impacts in smog and respiratory effects compared to other waste treatment options.

Moreover, because of the unique features of CLT panels, it is appropriate to reuse the panels after a building is demolished. Applying CLT for secondary use in nearby construction projects can reduce the environmental impacts from transportation and waste processing. Reusing 36% of the CLT materials can substantially reduce the environmental impacts compared to landfill disposal or incineration alone.

The results of this chapter did not include the fact that, the carbon stored in the product is released to the atmosphere with either landfill disposal or incineration, ending the two-way flow cycle of carbon first taken from and ultimately returned to the atmosphere. Under sustainable forest management, the carbon removed is equal to the carbon in the harvested wood, some of which is used for energy, while most is then stored in products for their useful life. Hence, the carbon stored result in a negative carbon technology - the opposite of fossil emissions that provide a one-way flow of carbon emissions from deep in the earth to the atmosphere that accumulates with time. But the product carbon storage ends with decomposition in the landfill or incineration in contrast to the potential for periodic reuse.

Contribution to environmental impacts such as global warming can be reduced when CLT is reused rather than disposed. In the landfill and incineration options, GWB and concrete play a significant role in impact contribution. This research assumes that GWB and concrete are landfilled, whereas in practice, these materials may also be partially recycled. Nonetheless, a challenge for CLT/concrete hybrid buildings is that, it is somewhat difficult to separate CLT materials from concrete and GWB after demolition, which limit the possibilities of reusing or recycling these materials. Because of this challenge, it is likely that a lot of reusable CLT material will be disposed along with materials such as concrete and GWB. To optimize the role of CLT in reducing negative environmental impacts, it is sensible to improve our knowledge toward the design and engineer of the buildings, for example, designing CLT buildings for easier disassembly, to make CLT reuse more feasible.

4.5. Future Research

This chapter did not consider alternative EoL options for materials other than CLT. For instance, different EoL options for concrete need to be considered to compare the differences in environmental impacts between treating building components with and without CLT substitution. The GWP may change if concrete is recycled instead of landfilled. Recycled concrete may be used in road pavement or aggregates, but often requires pre-handling that involves heavy duty equipment such as large industrial crushers that require significant amounts of energy. On the other hand, it is possible for CLT to be reused directly without additional industrial processes, which may significantly reduce the environmental impacts of CLT compared to landfill. Comparison of recycling and reuse options between concrete and CLT are not investigated in this research but should be considered in future studies.

4.6. Conclusion

The EoL system described in this chapter is a combination of three waste treatment options: landfill, incineration, and local reuse. The results show that reusing CLT materials has the potential of significantly reducing the environmental impacts of CLT at the EoL phase. Increasing the percentage of CLT reuse should be carefully considered as the future demand for CLT is likely to increase in cities. It is not clear how CLT will be reused in the future and therefore, this study did not account for the impacts from secondary uses of CLT. The impacts of CLT reuse will make a valuable topic for future studies.

Chapter 5: Summary and Conclusions

This chapter summarizes the results from the previous chapters. The main goal of this chapter is to draw conclusions from previous chapters and outline the significance of this research to the environmental impacts of forest and forest products.

5.1. Research Summary

The main focus of this research was to assess the environmental impacts of CLT production in western Washington and investigate the end-of-life treatment of CLT. Main tasks accomplished in this research include the following:

1. Provide regional and site-specific data associated with CLT production and model the environmental impacts of CLT that are associated with the logistics and wood species mix.
2. Identify the role of CLT in reducing construction waste and environmental impacts.
3. Identify major challenges associated with construction wastes and possible outcomes by increasing the use of CLT in construction.
4. Investigate the potential environmental impacts of CLT disposal in landfills and compared the impacts with those of concrete and steel.
5. Develop a case scenario for end-of-life treatment of CLT in Washington and modeled the environmental impacts.

In this research, under the baseline scenario described in Chapter 2, the total global warming impact of CLT production can range from around 163 to 202 kg CO2 eq., with transportation accounting for 4% to 24% of the overall impacts, depending on the location of the facilities. If only impacts associated with CLT (i.e. lamstock transport from sawmills, on-site CLT manufacturing, and CLT transport to construction site) are considered, transportation accounts for at least 7% of the overall environmental impacts. Wood species mix is also an influential factor in the CLT production process.

At the EoL phase, the environmental impacts of CLT panels depend on how and how much they are disposed of. The environmental impacts under the baseline EoL scenario described in Chapter 4 showed lower impacts in many impact categories as compared to landfill or incineration alone. Assuming a functional unit of 1 m^3, if all CLT is either landfilled or incinerated, the global warming impact under these two treatment scenarios are approximately 50 kg CO_2 eq. and 55 kg CO_2 eq., respectively, whereas the combined scenario only has a global warming impact of 43 kg CO_2 eq. Another thing to note is that, transportation accounts for 41% of the overall impacts under the landfill only scenario, and 57% under the incineration only scenario. Under the baseline scenario, transportation accounts for 55% of the total impacts.

Although this research focused on the emissions of CLT and did not get into details about the carbon storage aspects of products, it is important to note that the carbon storage benefit of wood products should not to be neglected. Table 5.1 and 5.2 provide a summary of the net CO_2 that is stored in the product over the phases considered in this research. These numbers can be used in future research where the carbon benefit of CLT is incorporated. The carbon stored in CLT was also discussed in Chapter 4.

Table 5.1. CO_2 stored in the product and net CO_2 during the production phase.

	Lumber Production (Unit: 1.21 m^3)	**CLT Manufacturing (Unit: 1 m^3)**	**Transportation (Lumber + CLT)**	**Transportation (Mid-Range)**	**Total (Mid-Range)**
kg CO_2 Emission	58.94	96.71	7 to 47	27	183
kg CO_2 in Product	1,034	854	-	-	854
Net kg CO_2	975	757	-	-	671

Table 5.2. CO_2 stored in the product and net CO_2 during the EoL phase (unit: 1 m^3 of CLT).

	Landfill	Incineration	Reuse
kg CO_2 Emission	49.57	55.23	21.35
kg CO_2 in Product	-	-	854
Net kg CO_2	-	-	833

5.2. Conclusion

5.2.1. The role of sawmill locations and wood species mix

As a wood product, CLT possess many carbon benefits. For instance, CLT continues to store carbon after the trees are harvested and can offset some of the carbon released during manufacturing. As described in Chapter 2, the environmental impacts can vary significantly when one of the parameters changes. For example, using lumber (CLT lamstock) from a nearby sawmill can significantly reduce the environmental impacts of CLT production. Another interesting finding is that the wood species mix used for lamstock is an important factor associated with the environmental impacts of CLT manufacturing. As presented in this research, using Sitka spruce as the raw material for lumber produces lower total environmental impacts compared to the baseline scenario where a 50-50 mix of Douglas-fir and western hemlock is used. Assuming all other factors remain constant, the wood species mix plays an important role in CLT production and may offset the higher environmental impacts generated from longer transportation distance. Thus, establishing a CLT manufacturing in an area with nearby lumber suppliers and lighter wood species can help improve the environmental benefits of using CLT.

5.2.2. Emissions from Disposal

CLT is a relatively new product to the U.S. construction industry and its impacts at the local and regional-level are not well understood. Nonetheless, it has the potential of becoming one of the mainstream construction materials for many reasons. For example, demand for tall buildings in population-dense cities makes finding lighter alternative materials a crucial step in mitigating the rising concerns toward the treatment of C&D wastes. Chapter 3 provided an overview of the current waste generation and treatment in Washington State, and projected future C&D waste generation. As future demand for CLT shows strong potential, it can reduce the amount of waste associated with C&D.

As compared to buildings with concrete and steel, building with CLT panels requires less material to serve the same structural function, and therefore, leads to a reduction in waste. Under a baseline scenario where all building materials are disposed in landfills, CLT panels produce lower CO_2 emission as compared to concrete because carbon emitted from woods is considered biogenic. On the other hand, methane emission tends to be higher for CLT as compared to concrete within a 100-year timeframe because wood decomposes at a higher rate than concrete. To avoid higher methane emission, it is rational to increase wood recycling and reuse to reduce the carbon footprint of using CLT in the construction industry.

5.2.3. End-of-Life of CLT

Chapter 4 modeled the potential environmental impacts of CLT at the EoL phase using a waste treatment scenario that is feasible in the State of Washington, that is, assuming 40% of the CLT is disposed of after demolition, 36% goes to incineration, and 24% is reused or resold locally. By combing three waste treatment options, lower environmental impacts may be achieved. For instance, disposing of all materials in a landfill generates the highest eutrophication potential. By diverting some of the CLT materials to incineration or reuse, the eutrophication potential is significantly reduced. Due to the use of wood adhesives, the incineration of CLT can also lead to a high smog potential and respiratory effects. This research suggests that increasing the rate of direct CLT reuse can reduce the harmful environmental impacts. For example, applying CLT from a demolished building directly to another construction project can limit the environmental impacts from transportation and processing. The secondary uses of CLT depend on future technology and regulations, which require further investigation. It is important to note that, by accounting for the carbon content stored in the CLT, the reuse option would result in negative net carbon emissions (Table 5.2), assuming the wood was harvested in sustainably managed forests.

5.3. Implications and Contributions

The use of alternative materials beyond concrete and steel is an effective way to mitigate environmental impacts. CLT can potentially innovate the construction industry by providing a lighter and more sustainable alternative material option for construction. Nonetheless, the lack of region-specific knowledge associated with the production and EoL treatment of CLT may be important factors that prevent the developments of CLT in many regions of the U.S. These research gaps have not been addressed in existing studies. The data and results presented in this research provide references regarding the environmental aspects for developing CLT production and EoL treatment. These results are particularly important for the State of Washington, which has rich forest resources and has begun developing a CLT industry. This research can help the wood product industry, facility operational managers, researchers, and the public to achieve a better understanding regarding the production and disposal of CLT.

5.4. Limitations and Future Research

The focus of this research was the carbon emission of CLT production and disposal, and did not include the carbon sequestration and the displacement factor associated with CLT. It should be noted that the environmental impacts of CLT may be reduced if these factors are included. For instance, the displacement of wood products and bioenergy for non-wood alternatives and fossil fuel would increase the carbon benefits of using CLT panels. By accounting for the displacement of fossil-intensive materials with wood products, the carbon benefit of using CLT may be more than enough to offset the emissions from production, assuming the raw materials are harvested from sustainably managed forests. In addition, this research did not compare the environmental impacts of CLT with alternative materials such as concrete. A comparative LCA study is needed to compare the environmental advantages and limitations of using CLT instead of other construction materials. These aspects should be incorporated in future CLT research.

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Appendix A

Major contributing substances (0.01% cut-off) of 1 kg of CLT to different environmental impact categories under the incarnation scenario.

(a)

Substance (kg CO_2 eq.)	**Resin**	**Wood**	**Total**
Carbon dioxide, fossil	0.034017	0.008988	0.043005
Dinitrogen monoxide	0.003803	0.004388	0.008191
Methane, biogenic	1.02E-06	1.39E-05	1.5E-05
Methane, fossil	7.4E-05	0.000519	0.000593
Sulfur hexafluoride	6.44E-07	5.02E-06	5.66E-06

(b)

Substance (kg SO2 eq.)	**Resin**	**Wood**	**Total**
Ammonia	2.68E-07	1.44E-06	1.71E-06
Hydrogen chloride	2.05E-07	4.65E-07	6.7E-07
Hydrogen fluoride	9.63E-09	2.91E-07	3.01E-07
Hydrogen sulfide	1.79E-08	1.16E-07	1.34E-07
Nitrogen oxides	2.82E-05	0.000131	0.000159
Sulfur dioxide	3.54E-06	2.34E-05	2.69E-05

(c)

Substance (kg O_3 eq.)	Resin	Wood	Total
Chlorine	2.95E-07	1.12E-06	1.42E-06
Nitrogen oxides	0.000998	0.004637	0.005635
Toluene	6.16E-08	5.37E-07	5.99E-07

(d)

Substance (kg N eq.)	Resin	Wood	Total
Ammonia	1.69E-08	9.11E-08	1.08E-07
Ammonium, ion	8.3E-09	3.49E-08	4.32E-08
BOD5, Biological Oxygen Demand	1.69E-06	7.21E-05	7.38E-05
COD, Chemical Oxygen Demand	4.02E-06	0.000173	0.000177
Nitrate	9.87E-06	1.15E-05	2.14E-05
Nitrogen	1.24E-08	6E-08	7.24E-08
Nitrogen oxides	1.78E-06	8.28E-06	1.01E-05
Phosphate	1.08E-06	4.85E-05	4.96E-05
Phosphorus	5.61E-11	1.23E-07	1.23E-07

(e)

Substance (kg CFC-11)	Resin	Wood	Total
Ethane, 1,1,1-trichloro-, HCFC-140	1.55E-14	1.25E-13	1.41E-13
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	4.14E-13	3.21E-12	3.63E-12
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	2.4E-12	2.03E-11	2.27E-11
Methane, bromochlorodifluoro-, Halon 1211	2.88E-11	1.98E-10	2.27E-10
Methane, bromotrifluoro-, Halon 1301	1.25E-10	8.39E-10	9.64E-10
Methane, chlorodifluoro-, HCFC-22	1.43E-12	3.44E-11	3.59E-11
Methane, dichlorodifluoro-, CFC-12	1.25E-12	8.23E-12	9.48E-12
Methane, monochloro-, R-40	6.85E-13	5.52E-12	6.21E-12
Methane, tetrachloro-, CFC-10	2.99E-11	7.33E-11	1.03E-10

Appendix B

Major contributing substances (0.01% cut-off) of 1 kg of CLT to different environmental impact categories under the landfill scenario.

(a)

Substance (kg CO_2 eq.)	Resin	Wood	Total
Carbon dioxide, fossil	0.00045	0.010004	0.010454
Carbon dioxide, land transformation	3.6E-07	8.46E-06	8.82E-06
Dinitrogen monoxide	1.78E-05	0.000118	0.000135
Methane, biogenic	5.19E-07	0.050727	0.050728
Methane, fossil	0.000876	0.000552	0.001428
Sulfur hexafluoride	5.36E-07	1.08E-05	1.14E-05

(b)

Substance (kg SO_2 eq.)	Resin	Wood	Total
Ammonia	4.53E-08	5.19E-07	5.64E-07
Hydrogen chloride	1.26E-07	5.95E-07	7.21E-07
Hydrogen fluoride	4.99E-09	2.9E-07	2.95E-07
Hydrogen sulfide	7.78E-10	3.51E-08	3.59E-08
Nitrogen oxides	1.02E-06	5.39E-05	5.49E-05
Sulfur dioxide	7.21E-07	2.93E-05	3E-05
Sulfur oxides	2.16E-10	1.51E-08	1.53E-08

(c)

Substance (kg O_3 eq.)	Resin	Wood	Total
Butane	4.83E-09	3.08E-07	3.13E-07
Ethene	5.12E-09	3.32E-07	3.37E-07
Formaldehyde	7E-09	4.24E-07	4.31E-07
Nitrogen oxides	3.62E-05	0.001907	0.001943
Pentane	7.03E-09	4.49E-07	4.56E-07
Propene	3.04E-09	1.99E-07	2.02E-07
Toluene	4.73E-09	2.29E-07	2.34E-07
Xylene	8.97E-09	3.57E-07	3.66E-07

(d)

Substance (kg N eq.)	Resin	Wood	Total
Ammonium, ion	0.000272	0.000311	0.000583
BOD5, Biological Oxygen Demand	2.95E-05	0.001296	0.001325
COD, Chemical Oxygen Demand	0.000125	0.005481	0.005605
Nitrate	1.74E-05	2.52E-05	4.26E-05
Nitrogen	2.77E-07	5.21E-07	7.99E-07
Nitrogen oxides	6.46E-08	3.41E-06	3.47E-06
Phosphate	5.03E-07	1.9E-05	1.95E-05

(e)

Substance (kg CFC-11 eq.)	Resin	Wood	Total
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	2.13E-13	6.36E-12	6.58E-12
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	1.48E-12	4.3E-11	4.45E-11
Methane, bromochlorodifluoro-, Halon 1211	1.24E-12	3.65E-11	3.78E-11
Methane, bromotrifluoro-, Halon 1301	5.22E-11	3.47E-09	3.52E-09
Methane, chlorodifluoro-, HCFC-22	2.07E-13	1.02E-11	1.04E-11
Methane, dichlorodifluoro-, CFC-12	2.9E-13	1.06E-11	1.09E-11
Methane, monochloro-, R-40	5.89E-13	1.15E-11	1.21E-11
Methane, tetrachloro-, CFC-10	8.69E-14	4.78E-12	4.87E-12

VITA

I am a member of the Center for International Trade in Forest Products (CINTRAFOR) lab at the University of Washington. My past research topics included mass timber, wood product trade, environmentally certified wood products, and environmental risk assessment associated with water and air pollution. I completed my masters and undergraduate studies at the University of California, Irvine.