AN ABSTRACT OF THE THESIS OF

Pantea Mirzaie for the degree of Master of Science in Industrial Engineering presented on May 28, 2013

Title: A Supply Chain Model for Optimizing Fixed and Mobile Bio-Oil Refineries on a Regional Scale

Abstract approved:

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The use of fossil fuels and their related impact on the environment and global warming have encouraged societies to pursue more sustainable and renewable alternatives, e.g., forest-based bio-oil. Thus, a vital need to decrease the level of greenhouse gas emissions and the tendency of nations to reduce their dependency on imported oil have created a new mission for society: To increase the robustness of the environmental and economic aspects of woody biomass to bio-oil supply chains. Prior studies have focused on developing novel methods and approaches for improving single stages of biomass supply chains. Others have focused on ameliorating biomass supply chain performance from a systems perspective for a host of different biomass types, e.g., agricultural residues and forest residues, and logistics issues, e.g., transportation distance and storage.

Bio-oil can be produced from woody biomass through the fast pyrolysis process, among different methods. Mobile processing has been developed in recent years to facilitate bio-oil production from woody waste and to reduce overall bio-oil supply chain cost, however, questions surrounding the environmental and economic benefits of using mobile processing plants in combination with large-scale non-mobile (fixed) processing plants remain unanswered.

The research presented develops a mathematical model capable of assisting decision makers in determining the optimal combination and location of fixed and mobile bio-refinery plants for a known woody waste supply stream and set of harvesting areas. The major cost elements in the optimization model are transportation costs and capital costs. The model is applied to hypothetical case for northwest Oregon by using historical harvesting data for state-owned and private forests in the region. Distances between locations are obtained by using a geographical information system to elucidate roadway effects. The model is optimized for cost by using an integer linear programming solver. Supply chain environmental impacts are then assessed by considering the carbon footprint (CO_2 equivalent mass) of transportation activities and the bio-refinery infrastructure. Sensitivity analysis is conducted for six major factors within the mathematical model to assess their effects on the estimated supply chain cost and carbon footprint, as well as on the number and location of the mobile and fixed bio-refineries.

The application of the model indicates that the utility of a mobile processing plant aligned with a fixed processing plant is more obvious when transportation cost and distance increase. In addition, this study seems to confirm the premise that transferring bio-oil to a processing facility is often more preferable than transporting woody biomass. However, results indicate that the capital intensity (cost and environmental impact) of mobile processing plants can greatly degrade their relative utility within a mixed mode supply chain.

A Supply Chain Model for Optimizing Fixed and Mobile Bio-Oil Refineries on a Regional Scale

by
Pantea Mirzaie

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APPROVED:

Major Professor, representing Industrial Engineering

Head of the School of Mechanical, Industrial and Manufacturing Engineering

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Pantea Mirzaie, Author

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bu_{p_b}	Biomass storage at a fixed plant
C_{m_f}	Operational cost of in-forest tractor-trailer ($)
C_{m_r}	Operational cost of highway trailer ($)
$C_{m_{ta}}$	Operational cost of bio-oil tanker ($)
C_{p_b}	Overall cost of a fixed plant (including capital and operational costs) ($)
C_{p_m}	Overall cost of a mobile plant (including capital and operational cost) ($)
$C_{bu_{p_b}}$	Capital cost of biomass storage at a fixed plant ($)
$C_{s_{p_b}}^{bio\text{-}oil}$	Capital cost of bio-oil storage at a fixed plant ($)
$C_{I_{bu_{p_b}}}$	Inventory cost of woody biomass
D_{fr_d}	Distance between harvesting area to nearest main road (miles)
$D_{r_d bu_{p_b}}$	Distance between main road and a biomass storage at a fixed plant (miles)
$D_{p_m p_b}$	Distance between a mobile plant and a fixed plant (miles)
f	Harvesting area
k	Expected operational life of a processing plant
m_f	In-forest tractor-trailer
m_r	On-road or on-highway tractor
m_{ta}	Bio-oil tanker

LIST OF PARAMETERS (Continued)

p_b	Fixed processing plant
p_m	Mobile processing plant
$q_{p_m t}$	Processing rate of a mobile plant in time t (US tons)
$q_{p_b t}$	Processing rate of a fixed plant in time t (US tons)
$q_{bu_{p_b} t}$	Capacity of biomass storage at fixed plant at time t
r_d	Nearest main road to harvesting areas
s_{p_b}	Bio-oil storage at a fixed plant
t	Time
ω_{m_f}	Capacity of in-forest tractor-trailer (US tons)
ω_{m_r}	Capacity of highway trailer (US tons)
$\omega_{m_{ta}}$	Capacity of bio-oil tanker (US tons)

LIST OF VARIABLES

$I_{bu_{p_b}t}$	Amount of woody biomass stored in time t
$j_{bu_{p_b}p_bt}$	Amount of woody waste transferred from biomass storage to fixed plant p_b at time t
$n^{fr_d}_{m_ft}$	Required number of in-forest tractor-trailers to transfer woody waste form harvesting area f to nearest road r_d at time t
$n^{r_dbu_{p_b}}_{m_rt}$	Required number of on-road trailers to haul the amount of woody waste from road r_d to biomass storage at fixed plant $p_b$at time t
$n^{p_mp_b}_{m_{ta}t}$	Required number of bio-oil tankers to transport produced bio-oil from mobile plant p_m to fixed plant p_b at time t
$n^{fp_m}_{m_ft}$	Required number of in-forest trucks to haul the determined amount of woody biomass form harvesting area f to mobile plant p_m at time t
$X_{fbu_{p_b}t}$	Amount of woody waste transferred from harvesting area f to biomass storage at fixed plant p_b at time t
X_{fp_mt}	Amount of woody waste transferred from harvesting area f to a mobile plant p_m at time t
$Y_{p_mp_bt}$	Amount of bio-oil transferred from mobile plant p_m to fixed plant p_b at time t
Y_{p_bt}	Amount of bio-oil produced by fixed plant $p_b$at time t
$\tau_{p_m} \begin{cases} 1 \\ 0 \end{cases}$	If mobile plant is working, otherwise

LIST OF VARIABLES (Continued)

$$\varphi_{p_m} \begin{cases} 1 & \text{If fixed plant is working,} \\ 0 & \text{otherwise} \end{cases}$$

Chapter 1 - Introduction

This chapter contains the motivation drivers for accomplishing the research addressed in this thesis. It provides the research problem and thesis objective in addition to an outline for the thesis.

1.1 Motivation

Coal, petroleum, natural gas and all other types of fossil fuel are considered primary sources of energy for electricity generation, automobiles, burners and other energy consuming products. However, fossil fuel depletion and its impact on the environment and climate have forced societies to substitute this source of energy with renewable sources that exhibit better sustainability performance. Bio-fuels, for example, are provided by different types of biomass and have gained much attention in recent years. An analysis conducted by the United Nations Conference on Environment and Development (UNCED) has estimated that by the year 2050 approximately half of the primary energy consumption of the world will be supplied through biomass resources (Demirbaş 2001).

A vital need to decrease the level of greenhouse gas (GHG) emissions and the need for nations to reduce their dependency on imported energy sources have created a new mission for many regions and countries: To enhance the economic and environmental aspects of the biomass to bio-oil supply chain.

Bio-oil is one type of renewable bio-energy that can be produced from woody biomass, including wood waste. The combustion of unusable forest products that have the potential of being considered either as by-products or fire hazards is nearly carbon neutral (Steele et al. 2012). Hence, bio-oil from forest wastes is seen as a promising source of renewable energy for society when considering its environmental, economic, and social benefits. With a sharp increase in the trend to substitute bio-oil for fossil-based fuel, more bio-refinery plants are needed to meet the demand for bio-oil and bio-fuels. As a result, assessing and optimizing supply chains for the conversion of woody biomass to bio-oil is also required from a sustainability perspective in order to provide the market with the most economically viable, environmentally friendly, and socially acceptable products.

This research is motivated by the premise that bio-oil fuel can be represented as an economically accepted and technically feasible alternative for fossil fuel-based applications. However, the quantity of the output produced from woody biomass is not sufficient to satisfy the current demand of petroleum due to costs related to its transportation and the lack of available bio-refineries (Sokhansanj, 2002). One major idea that has been recently developed is the application of small-scale transportable woody biomass processing plants that can be settled in forests and deployed to produce bio-oil (ROI, 2003). If mobile processing plants can integrate with non-mobile (fixed) processing plants, the limitation of producing adequate quantities of bio-oil can be overcome, and this alternative fuel can be utilized more efficiently and effectively.

1.2 Background

The unstable price and non-renewable nature of fossil fuels, in addition to their potential effects on the environment and climate have directed society to substitute a greater portion of conventional fuels with renewable fuels. As a result, many actions have been applied to different stages of the bio-fuel supply chain, such as a focus on optimal transportation and storage, to increase reliability and cost efficiency. Storage issues have been analyzed by a number of researches to investigate potential locations for storage and different storage layout suitable for storing the agricultural biomass. Moreover, different methods of harvesting and collection have been studied to reduce the cost of transportation and storage for switchgrass biomass.

Woody biomass, as another example of biomass, has gained attention due to its widespread nature and potential use of a bio-oil fuel. However, due to moisture content level of each wood and energy density of different forms of woody biomass, such as woody chips, woody pellets and cubes, the quality and the final cost of the production is different.

Low yield and poor bio-oil quality is one of the main challenge addressed through considerable research efforts. Different bio-oil quality improving processes, such as hydro-treating and hydro-cracking, have been developed to overcome low bio-oil quality in the aim of producing an appropriate alternative fuel for petroleum based applications (Xiu and Shahbazi 2012). On the other hand, numerous methods and models, such as applying mobile chippers or utilizing transportable processing plants, have been developed in biomass to bio-oil supply chains to decrease the final cost of bio-oil production. However, some gaps exist in the analysis of bio-oil supply chains that must be addressed to ensure they are robust, dependable, and sustainable.

The novel idea of producing bio-oil from woody biomass through the use of mobile refineries has been studied from an economic perspective. The aim of previous researches has been to prove the role of small-scale transportable plant in decreasing total supply chain cost. However, research into the optimal combination of mobile and non-mobile (fixed) refineries from an economic and environmental perspective is deficient.

1.3 Problem Description

To improve bio-oil supply chain networks and to be able to respond to rapid increases in fuel consumption, different supply chain schemes with a combination of current processing, technologies are needed. The mixed model bio-oil supply chain, consisting of both mobile and fixed bio-refinery plants, may be crucial in meeting consumer fuel demands. This situation is explored in this thesis by developing and examining an optimal regional economic and environmental bio-oil supply chain approach.

1.4 Research Task

The research presented herein undertakes several research tasks to address the problem identified above. First, it will provide a comprehensive review of prior research within the period of 1989 to 2013 to identify the current methods and approaches for bio-mass processing technology and supply chain optimization. Additionally, it will identify the existing deficiencies within bio-mass modeling logistics. Current practice for storage locations and types, optimal processing and storage capacity, transportation optimization model and supply chain technologies will also be addressed.

The second task is to develop a mathematical model to estimate the capital and transportation costs for a combination of fixed, large-scale bio-refinery plants and mobile, small-scale bio-refinery plants, used to produce bio-oil from woody biomass. This model will be used to support the third research task, which is to assess the economic and environmental impact of different scenarios through the application of a real world case. This application will also reveal the sensitivity of results to modeling assumptions, which will lead to recommendations for future research.

This work aims to improve the robustness and sustainability of bio-oil supply chains through defining the optimal number and location of mobile and fixed bio-refineries from a system-level cost perspective, while assessing the relative environmental impacts of the various scenarios examined. This work will lay the foundation for a broader sustainability-based optimization of regional bio-mass supply chains by utilizing a variety of processing technologies.

1.5 Thesis Outline

The research in this thesis is reported in the standard format, and composed of five chapters. The current chapter (Chapter 1) provides the motivation behind the research conducted in this thesis, gives a description of the research problem under investigation, and outlines the objectives and chapter flow. Chapter 2 provides a literature review of prior work related to bio-mass to bio-fuel supply chain assessment and bio-oil production, and introduces the method developed and applied in later chapters. Chapter 3, the methodology, develops a mathematical model to optimize a combination of fixed and mobile bio-refineries by considering the capital and transportation costs of the bio-mass processing system. Chapter 4, a demonstration of the method, concentrates on applying the cost optimization model to a specific, but hypothetical, case for northwest Oregon, and implementing sensitivity analysis by considering the most impactful factors in decision making. The effects of several factors on cost and carbon footprint are explored in the sensitivity analysis. Chapter 5 summarizes and concludes the research discussed in previous chapters and offers recommendations for future work to improve on the findings and carry the research forward.

Chapter 2 - Literature Review

According to the U.S. Energy Information Administration (EIA), 83% of energy consumption in United States is provided through fossil fuels including natural gas, coal, and petroleum, with petroleum as a dominant source of energy (U.S. EIA, 2011). About 8% of the total energy supply in the United States is from renewable energy sources such as wind, biomass, solar, geothermal and hydropower which provide a small but steadily increasing portion of U.S. energy consumption. The non-renewable nature of fossil fuels, along with their environmental impacts, e.g., greenhouse emissions (GHG), in addition to the need of a society to reduce its dependency on fossil fuel, however, has encouraged substitution of a greater portion of fossil fuel with renewable energy sources (Zhang, et al., 2011; Xiu and Shahbazi, 2012). A motivation for pursuing alternative sources of energy in United States was the energy crises in the 1970s, when the government encouraged the substitution of renewable energy sources in place of fossil fuel (Oasmaa and Czernik 1999).

Woody bio-mass has gained much attention as a source of renewable energy in recent years due to its availability across the world. According to statistics that have been released by the Food and Agricultural Organization, the area of the forested land worldwide is estimated to be 38.7 Tm^2 which consists of 95% natural forest and 5% plantation land (SOFA, 2003). This could be considered as a great opportunity in using woody biomass as a source for thermal energy, electrical energy, and fuel.

The objective of this literature review is to explain how woody biomass can be utilized optimally by improving different stages of the supply chain. This literature review will focus on the strength and weakness of prior research; different methods such as Geographical Information Systems (GIS) and mathematical modeling applied in prior research will be discussed to highlight the current pitfalls. This review will also lead to a new approach for modeling and optimizing the woody biomass to bio-oil supply chain from a broader sustainability perspective.

2.1 Biomass and Bio-fuels

One of the main factors on which a sustainable society must be based is achieving optimal use of renewable energy sources. According to the U.S. Energy Information Administration (EIA), biomass energy consumption is trending to increase by 4.4% annually through 2030 (U.S. EIA, 2009). As a result, it is predicted that biomass consumption would account for 20% of renewable energy sources by that time (Wright et al. 2010). This increase in the level of substitution for conventional energy not only relates to the renewable and carbon-neutral nature of the biomass resource, but it is dependent upon the availability of biomass nationwide, including woody biomass in the State of Oregon.

In order to understand the nature of bio-energy, it is important to discuss the biomass resources that will be used in an energy conversion center (Frombo et al. 2008). Various types of biomass, such as agricultural, municipal, and forest biomass, will need to be processed in order to produce different types of bio-fuels.

Traditionally, agricultural products, e.g., corn and soybeans have been used to produce bio-fuels, such as bio-ethanol and bio-diesel. However, for several reasons the supply and cost of agricultural biomass is often uncertain: (1) the food versus the fuel controversy, (2) the high cost of transportation, (3) storage cost due to their seasonal availability, and (4) weather conditions (Eksiog¢lu et al., 2009). These challenges have encouraged producers to investigate other biomass options. Recent studies are focusing on using waste biomass such as forest residues, agricultural residues, and municipal waste to produce bio-energy (Aden et al. 2002).

As reported by a USDA forest service report (USDA, 2003), approximately 73 million acres of national forest lands, mostly in the Western region, have an excessive amount of woody biomass that has the potential to be used as a feedstock for bio-oil production, since this enormous portion of degradable products would lead to catastrophic forest fires (Dumroese et al. 2009). Another way to reduce forest fire hazard is to focus on thinning trees, which also creates another opportunity for producing bio-oil from woody waste (Nicholls, 2008).

Bio-fuel can be classified into four major types with different characteristics. The following section will explain the process and attributes of each fuel in detail.

2.1.1 Bio-fuel Classification

Bio-fuel can be categorized to different types of fuels with different attributes, e.g., bio-ethanol, bio-methanol, bio-diesel, and bio-oil. The process of creating bio-ethanol from cellulosic crops is similar to the process in brewing beer (Farag et al., 2001). Ethanol is one of the most accepted bio-fuels that can be considered as a substitute for gasoline (Brady, 2002). Bio-methanol, another type of bio-fuel, is similar to bio-ethanol. According to Brady (2002) this product is not suitable to be used alone, however, it can be added to gasoline.

Unlike bio-ethanol and bio-methanol, which are alcohols, bio-diesel is an ester and is used in marine engines, boats and launches (Brady, 2002). The high energy density of this product is a convincing reason to choose this fuel over other types of bio-fuel, especially bio-oil. For a better understanding of the level of energy density of each bio-fuel, their heating values are reported in Table 2-1.

Bio-oil is much different than the previous fuels discussed and is produced from degradable biomass via the fast pyrolysis process which will be further explored in the following section. The most common feedstock used for the production of this dark brown liquid fuel is woody waste, especially in a region where a large availability of forested land exists.

Table 2-1 Heating value comparison for different types of bio-fuels

Liquid Fuel	Heating Value (MJ/kg)	Heating Value (Btu/gal)
Bio-ethanol[1]	23.5	62,500
Bio-methanol1	17.5	84,000
Bio-diesel[1,]2	32.27	127,960
Bio-oil (wood)[2]	18-21	75,500

2.1.2 Fast Pyrolysis Process

Fast Pyrolysis process is a thermal process in which biomass is rapidly and indirectly heated at 400-800 °C in the absence of oxygen (Xiu and Shahbazi 2012). The products of this procedure, after a cooling stage, are bio-oil, bio-char and syngas. A percentage of the required thermal energy for the fast pyrolysis process can be satisfied through the use of syngas instead of supplying natural gas. Bio-char and bio-oil have gained attention from external markets, as they can be used as industrial fuels. Figure 2-1 illustrates the simplified process.

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[1] M.A. Elsayed, R. Matthews, and N. D. Mortimer, (2003), *Carbon and energy balances for a range of bio-fuels options*.
[2] Ensyn Group, Inc., (2001), *Bio-oil Combustion Due Diligence: The Conversion of Wood and Other Biomass to Bio-oil*

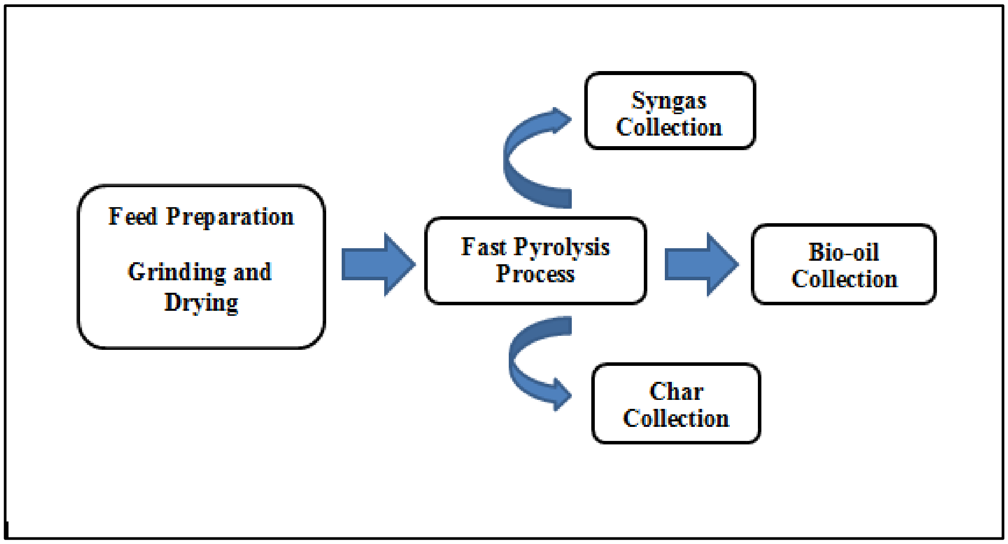

Figure 2-1- Simplified pyrolysis process

The major steps for the pyrolysis process, as shown in Figure 2-1, are biomass pretreatment, fast pyrolysis, removal of solids, and oil collection (Wright et al. 2010). Drying and resizing woody waste in the pre-treatment phase are the first and the most important activities in the fast pyrolysis process, since moisture content (MC) and the size of the biomass will have effect on the bio-oil yield. Moisture content of the biomass is a characteristic that not only could influence the chemical nature of the bio-oil produced, but effects the mass needed to be transported (Frombo et al., 2008).

Bio-oil can be stored and used as a substitute for diesel and fuel oil in many industrial applications such as boilers, furnaces, and turbines (Gust, 1997; Solantausta et al., 1993; Strenziok, et al., 2001). Due to bio-oil specification, however, this product cannot be used as a high quality fuel before further processing. According to Xie and Shahbazi (2012) bio-oil cannot directly substitute petroleum nor be used as a transportation fuel right after fast pyrolysis due to its high levels of water and ash, high viscosity, and low heating value. Therefore, the upgrading of bio-oil is needed if the aim of producing bio-oil is to provide transportation fuel. Several technologies, such as hydro-cracking and hydro-treating, have been developed to improve these processes. Research conducted as a part of this thesis does not focus on the upgrading process of bio-oil in the supply chain, and will limit analysis to the first phase of the process – biomass collection, transportation, and conversion to bio-oil.

Rather than bio-oil, there are various forms of fuels that are supplied through forest residues, but they are less popular due to their low energy densities when compared to bio-oil. The following section will highlight several benefits of bio-oil over other forest fuel products.

2.1.3 Bio-oil Preference Over Other Forest Fuel Products

As stated earlier, due to the large availability of forested land in Oregon, the amount of woody waste that can be converted to bio-oil is considerable. The usage of low-grade wood chips that remain in the forest after thinning and timbering can play an important role not only in developing job opportunities but also improving the overall economy. The low energy density of forest biomass is counted as one of the disadvantages for its collection, transportation, and use as a fuel. Several technologies have been developed in order to densify (increase the density of) bulk biomass either by pelletizing, cubing, and baling the biomass (Badger and Fransham, 2006), or by producing bio-oil. When comparing the energy densities of each product, bio-oil can be considered the most preferable product from woody waste, though its production can be capital-intensive (Zhang et al. 2012). Table 2-2 reports the energy densities of various types of biomass to demonstrate the advantage of transporting bio-oil over other forest fuel products (Badger and Fransham, 2006).

Table 2-2 Energy densities for various forms of forest fuel products

Biomass	**Energy Density (MJ/kg)**
Green whole tree chips	8.53
Green whole tree chips	10.66
Loose, uncompacted straw or hay	15.51
Baled grasses	15.51
Solid wood, high density	17.06
Cubes	17.45
Pellets	17.83
Bio-oil	18.00

Several registered companies and developers are applying fast pyrolysis process to produce this forest fuel through gaining an advantage getting advantage due to the high energy density of bio-oil. The following section will introduce the current leaders and developers in this field.

2.1.4 Bio-oil Production Technology Development

DynaMotive and Ensyn are the industry leaders utilizing the fast pyrolysis process to produce bio-fuel from biomass in North America, though the number of companies that have adopted this process have been increasing in recent years (Farag et al., 2001). In addition to the large scale companies that are currently producing bio-oil and bio-char through fast pyrolysis, several other developers of this technology, such as Renewable Oil International LLC, have proposed mobile and transportable plants.

This idea has been developed in the aim of decreasing the cost of transporting and handling of woody biomass. With regard to the outspread nature and significant amount of woody biomass, the major cost of producing bio-oil from woody waste can be attributed to the collection and transportation of feed stock from harvesting area to the destination (Sokhansanj, 2002). The collection and transportation of biomass raw material are the expensive supply chain activities for several reasons, including moisture content, which adds to the transportation costs, number of required operations, which adds to the labor and capital costs, and low energy density of woody waste compared to liquid form, which adds to the both transportation and handling costs (Badger, 2002). The difference in the energy density of bio-oil and biomass is explained visually through Figure 2-2. A bio-oil tanker can haul more energy-equivalent when compared to a biomass trailer with the same capacity, thus more than one biomass trailer is needed to carry the same amount of energy. The following section will provide extra explanation about the mobile processing plant and studies that have been done in this field.

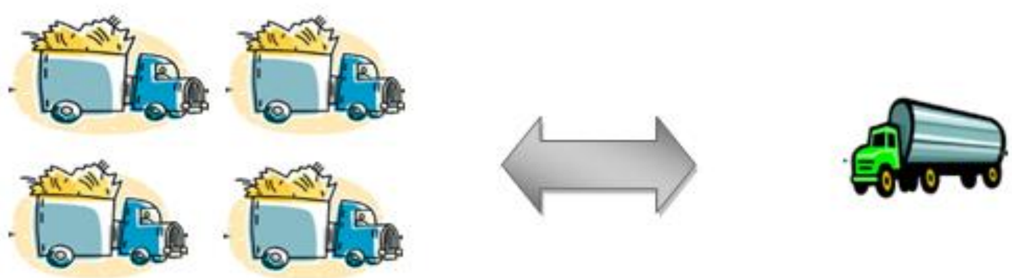

Figure 2-2 Comparison of hauling energy density through bio-oil tanker and biomass trailer with same capacity

2.1.5 Mobile Bio-Refinery Plant

The novel idea of a small scale mobile plant, using fast pyrolysis technology for transformation process, has been developed by the Renewable Oil International Company (Badger and Fransham 2006). The main motivation for this development is the difference in energy density between woody chips and bio-oil, which can have a significant effect on transportation costs in the biomass supply chain. Analytical supply chain modeling was carried out by Browne et al (1998) which could support the hypothesis that approximately 20-50% of the total cost of the biomass supply chain is the result of the transportation activities. One way to reduce the impact of this factor is to develop and implement new technology able to decrease the number of trips created by woody biomass transportation. By placing mobile bio-refinery plants next to collection areas or forest zones, the level of energy density that can be transferred per trip will increase.

The largest plant that ROI has fabricated is a wheel-mounted and transportable unit capable of processing woody biomass at rate of 15 tpd (bone dry tone per day)(Badger et al., 2011). Nevertheless, a financial model for a 50 tpd mobile unit has been developed by ROI (Dumroese, 2009) and the economic and technical feasibility of a 100 tpd plant has been analyzed by Badger et al. (2011).

An important question that has not been addressed in previous studies is: *How many mobile plants are needed to work simultaneously with a fixed plant to serve the total amount of woody waste in specific region?* This question can be answered by developing an optimization model focusing mainly on transportation costs, distance between harvesting area and processing plants, and the capital and operating costs of different processing plants.

Due to the novel nature of mobile processing plant, previous studies focusing on the development of mathematical model, have failed to cover this area of interest in the woody biomass to bio-oil supply chain. In addition, the idea of producing bio-oil from woody waste, either through a mobile or fixed processing plant, is a novel idea and few studies have paid enough attention to optimizing the supply chain both economically and environmentally when looking to decrease the overall cost of the system. The next section will discuss different steps in supply chain of woody biomass to bio-oil and explain current research gaps while reviewing the relevant literature.

2.2 Woody Biomass to Bio-oil Supply Chain

With an increasing interest in the use of biomass for energy, extensive literatures have focused on biomass logistics which have formed the foundation for developing the woody biomass to bio-oil supply chain model in this research.

As the demand of substituting conventional fuel with bio-energy has increased in recent years, the need to develop a robust and sustainable supply chain to deliver competitive bio-fuel to the market has become a challenge. The bio-fuel supply chain consists of a feed stock producer, transportation, storage, and bio-refineries that connect to the final product to the consumers. Several studies have focused on developing technological improvements in the process of transforming biomass to bio-fuels, while less focus has been placed on supply chain management. Establishing a robust, reliable, and sustainable bio-fuel supply chain can deliver a competitive end product to the market (Awudu and Zhang 2011).

Figure 2-3 shows a snap shot of a general bio-fuel supply chain. The network consists of several steps including: feedstock production (forest) and collection, transportation, storage, blending, and delivery to the end market.

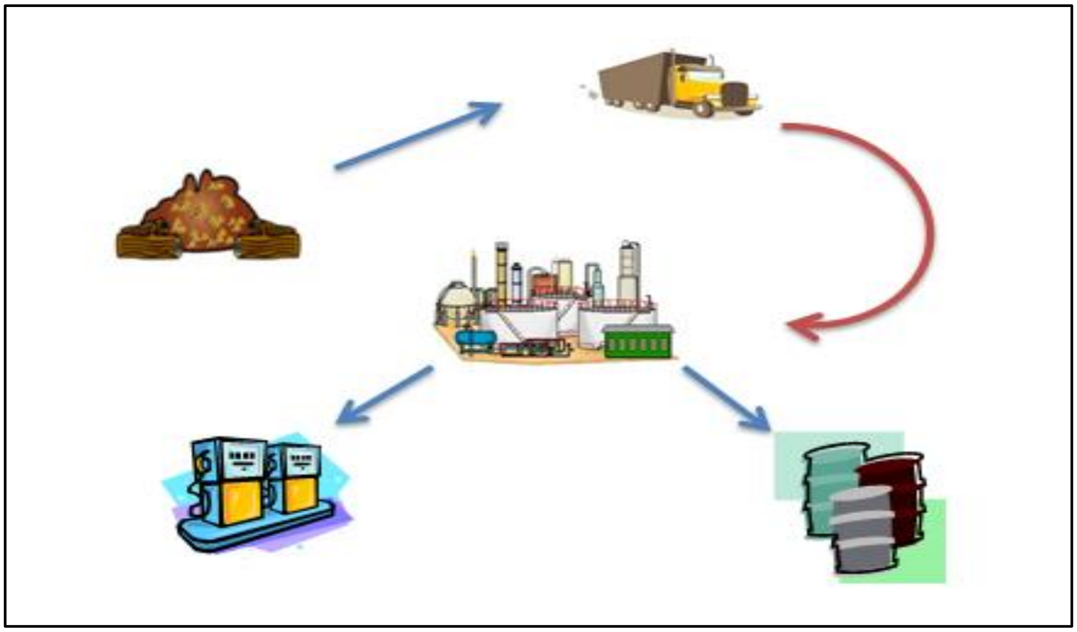

Figure 2-3 General bio-fuel supply chain network

Biomass raw materials are converted to bio-fuel, such as bio-oil, at bio-refineries. In general, the feed stock will be pretreated in the facility adjacent to the bio-refinery but in other cases, raw material will be transported directly from the field or forest to a bio-refinery. A bio-refinery plant will use various types of conversion technologies to transform different types of biomass into a range of end-products. The finished product will be transported to blending facilities if upgrading for quality improvement is intended.

It is apparent that an optimal bio-fuel supply chain is incumbent upon critical decision making in the collecting and purchasing of raw material, storage and facility location, processing facility size, and transportation network. This chain can be improved either by introducing new methodologies and techniques for each stage or by focusing on the whole supply chain from a system perspective. The following section will concentrate on studies that have focused on a single stage in the supply chain, and the next section will explore studies that have concentrated on the whole supply chain.

2.2.1 Analysis of a Single Stage in the Bio-fuel Supply Chain

The issues of storage locations and layouts, harvesting and collection methods, and delivery approaches have been investigated comprehensively by various authors. Storage problem is a major concern that threatens the quality of biomass logistics, especially when seasonal availability complicated the process. The availability of storage is one of the most critical decision making in the biomass supply chain due to its huge impact on the quality and availability of bio-fuel. However, valuable technological advances have been made that address the current obstacle. The location of storage has been investigated by a number of researchers, and in most cases, low cost storage solution have been identified (Rentizelas et al., 2009).

The impact of covered-on-field storage on the delivery cost of the herbaceous biomass has been discovered by Cundiff et al. (1997). While low storage cost can be obtained by applying this method, disadvantages of implementing the on-field storage scenario in the biomass supply chain are undeniable. A significant loss of biomass, the high moisture content of raw material and, risk of self-ignition and contamination are examples of potential problems for on-field storage. (Rentizelas et al., 2009)

Hence, the intermediate storage scenario has been analyzed by Tatsiopoulos and Tolis (2003). The disadvantage of applying this approach is related to increased transportation costs compared to the implementation of on-field storage in the supply chain. The reason for this additional cost is that transportation will be broken in to two separate phases: Transportation from the field to the storage facility and from the storage facility to the bio-refinery.

The third and final location to consider for storage is to settle the facility next to the bio-refinery. An innovative concept for the adjacent storage layout has been explored by Papadopoulos and Katsigiannis (2002), in which the required energy for drying the biomass stored in the facility can be provided by dumped heat from the heating plant. This approach is not only less environmentally impactful, but also more acceptable from an economic view, since biomass moisture will be evaporated without using an excessive amount of external energy.

Aligned with developing ideas about storage location, harvesting and collection approaches have been presented to create a deeper understanding of biomass logistics to address the storage problems not limited to forest residues. The cost of harvesting switchgrass and using an on field storage approach in the round bale style has been analyzed by Cundiff (1996) and an economic study of harvesting and storage methods for switchgrass in round and square style bales has been explored by Cundiff and Marsh (1996). Since square bales of switchgrass need to be stored in covered storage, this harvesting approach has difficulty competing economically with round style of switchgrass collection (Cundiff and Marsh 1996).

Work by Rentizelas et al. (2009) covered the other existing research gaps for storage aspects of biomass logistics. When considering multi-biomass, three types of storage layout, i.e., (1) adjacent warehouse with drying capability, (2) covered storage with metal roof and without drying infrastructure, and (3) ambient storage covered with plastic film, along with optimal storage capacity have been analyzed in their study. This study shows that the optimal biomass quantity for the third storage layout is greater when compared to other options due to the increased material losses even though the cost of handling and storing feedstock is less than the other layouts.

Handling and storage of woody biomass is attendant with concerns that differ from agricultural biomass. Woody biomass, for example, needs to be chipped after collection to achieve the proper characteristics for conversion into bio-oil. The decision of whether to implement centralized or decentralized chipper equipment has been analyzed by Gronalt and Rauch (2007) through a step-wise heuristic approach. In this model, a centralized chipper approach along with large capacity terminal for storing woody chipped has been compared with decentralized chippers serving several scattered terminals. The aim of this study was to determine the optimum forest fuel supply network by considering transportation, chipping, and overall cost of system.

Besides to other papers discussing the impact of individual stage on the bio-fuel supply chain, other studies have developed new methods and approaches to improve the biomass logistics from a system perspective. Next section will explore more about the role of different models on the improvement of the supply chain as a group of activities.

2.2.2 System Perspective of the Biomass Supply Chain

The study of optimization and dynamics models on the biomass supply chain has been conducted by several authors and organizations. Sandia National Laboratories provided a dynamics model that consider various types of biomass feedstock such as agricultural residues, forest residues and corn to produce cellulosic ethanol to meet the nation's goal of producing 90 billion gallons of bio-fuel by the year 2030 (West et al., 2009). The supply chain components included in this project were: production of biomass, storage and transportation of biomass, conversion of feedstock to ethanol, and transportation of ethanol to blending facilities. Potential barriers examined in this study include the transportation and distribution challenges, cost of feedstock, capital, energy and the greenhouse gas footprint.

Zhang et al. (2013) proposed a mixed integer linear programming (MILP) model that integrated all decision making related to harvesting, collecting, storage, and transportation of bio-ethanol and switchgrass to minimize the total cost of bio-ethanol supply chain. A case study in North Dakota has been applied to the presented optimization model to determine whether it is cost effective and sustainable to meet the annual energy demand of region through current bio-ethanol technology.

Zhu et al. (2011) analyzed a logistics system for dedicated biomass to the bio–energy supply chain in which restrictions on harvesting seasons and scattered geographical distributions were included. The application of the MILP model on the switchgrass biomass indicated that the operation of the system is highly depended on the harvesting and non-harvesting crop cycle and by applying a comprehensive logistic system, steady and sufficient quantity of bio-ethanol can be provided.

Erikson and Bjorheden (1989) presented a linear programming (LP) model to minimize the transportation cost of pellet fuel from several supply sites to a central heating plant. The optimal result of this mathematical model was to consider a direct transportation from the supply sites to the heating plant while using mobile chippers. However this model failed to help decision makers regarding whether to consider the use of additional harvesting areas or sawmills in the supply chain to meet the level of demand.

This drawback has been addressed by Gunnarsson et al. (2004) who developed a large and comprehensive MILP model for a forest fuel network where fuel will be produced from forest residues to support the demand of a combined heat and power (CHP) plant. The results of the mathematical model can be applied in decision making of when and where the plants should be placed, and if additional harvesting areas or sawmills are needed to meet the demand of the CHP plant.

2.3 Limitations of Prior Studies

Evaluation of previous research dedicated to biomass supply chain systems reveals gaps that need to be addressed. The research reported herein is intended to extend existing methods to overcome current challenges facing the woody biomass to bio-oil supply chain modeling and development.

The key differences between the reported mathematical optimization models and the one developed under this research are 1) prior models have not considered woody biomass as a source to produce bio-oil, and 2) the topic of a mobile plant aligned with a fixed plant has not been addressed. In addition, this research focuses on utilizing woody waste resulting from timbering and thinning activities in forests to provide inputs for the production of bio-oil.

The mathematical model presented in this study focuses on transportation costs, capital costs, and operation costs related to each processing plant in the system. The goal of the developed optimization model is to decide how many mobile and fixed plants are required to process the known amount of woody waste in the region while minimizing the total cost of the supply chain.

One important parameter in an optimization model for a combination of mobile and fixed plants is distance; and the major questions concern where to locate mobile plants and which harvesting areas should be chosen with regard to distance. The Geographical Information Systems (GIS) based approach has been widely used by different authors focusing on site locations and transportation costs. GIS is a system designed to capture, store, manage and analyze all types of geographic data and its ability to combine spatial information with quantitative and qualitative data-bases is accepted as one of its practical attributes (Zhang et al., 2011). Several studies have conducted research integrating the GIS approach with other qualitative and quantitative methods to make decisions regarding various location issues, such as landfill location and biomass field location.

Muttiah et al. (1996) used decision support systems including GIS algorithms to identify waste disposal sites. An allocation-location model integrating a GIS was used by Yeh and Chow (1996) to identify public facility location. Landfill diagnose method with the application of GIS was used by Zamorano et al. (2008)

to conduct a landfill site location assessment. GIS was also applied in the assessment of a geothermal field in Northwest Sabalan, Iran, to locate an appropriate site for exploratory wells (Noorollahi et al., 2008).

In the research presented herein, the main focus will be to investigate the optimal combination and location of fixed and mobile bio-refinery plants with regard to a known number of harvesting areas, volumes and locations. Different scenarios will be developed through the introduced mathematical model and, subsequently, the cost and environmental impact of each scenario will be evaluated for a specific region in northwest Oregon. Since distance is one of the major factors in deciding the number and location of fixed and mobile plants and in determining possible locations, GIS software will be implemented to calculate the shortest path between each harvesting area and facility location. The next chapter describes details of the model development and the following chapter demonstrates the model for the mixed mode bio-oil processing case.

Chapter 3 - Approach

As discussed in Chapter 2, the evaluation of supply chain model has been widely conducted in a variety of studies. However, the role of mobile processing plants in combination fixed processing plants for the improvement of the woody biomass supply chain is lacking. This chapter proposes a mathematical model approach capable of assisting decision makers in determining the optimal combination and location of fixed and mobile bio-refinery plants, with regard to fixed levels of woody waste supply and the location of harvesting areas. The first part of this chapter consists of an overview of the approach. The objective function and constraints of the proposed optimization model will then be explained in detail to prepare a background for assessing the environmental and economic effect of this model on a hypothetical case for northwest Oregon explored in Chapter 4.

3.1 Overview of the Approach

The optimization model presented as part of this research is a Mixed Integer Linear Programming (MILP) model. This model is developed to minimize the woody biomass to bio-oil supply chain cost by representing a binary variable for the operation of fixed and mobile plant in the model. Transportation costs, capital, and operational costs of the plants are the main contributors to this model. Since the feedstock for this process is woody waste, there is no purchasing cost involved in the overall cost of the supply chain.

The main purpose of this model is to estimate the required number and location of mobile and fixed bio-refinery plants to serve a known amount of woody waste. Hence, the mathematical model presented in this study will focus on the supply side of the woody biomass logistics and assumes demand exists for all bio-oil produced. As a result, bio-oil from mobile plant will be transported and the stored at the fixed plant locations, which are assumed to be the distribution points.

Section 3.2 will explore the formulation of the objective function in details followed by Section 3.3 which focuses on explaining the formulation of the objective function's constraints.

3.2 MILP Objective Function

The objective of the proposed MILP model is to minimize the cost of the woody biomass supply chain through the use of mixed mode bio-oil processing plants. The transportation costs of the supply chain include delivering woody waste from the forest to the mobile or fixed bio-oil processing plant using both in-forest and main roads and delivering bio-oil from the mobile plant to the bio-oil storage at fixed plant locations. The capital costs of the supply chain include establishment cost of fixed and mobile plants including operational costs, and the cost of biomass and bio-oil storage at fixed plant locations. Considering the above cost elements, the objective function (Z) to be minimized is shown in Equation (3.1); the different cost elements of the model will be explained in greater detail below.

$$\text{Min } Z = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7 + C_8 + C_9 \tag{3.1}$$

Equation (3.2) calculates in-forest transportation cost of delivering woody biomass from each harvesting areas to the main road, and is defined by D_{fr_d} (the shortest distance from the harvesting area to the road), C_{m_f} (operational cost of an in-forest tractor-trailer proper to haul woody waste in the forest), and $n_{m_f}^{fr_d}$ (required number of tractor-trailers to transfer available biomass).

$$C_1 = \sum_{m_f} \sum_{p_b} \sum_{f} D_{fr_d} . C_{m_f} . n_{m_f t}^{fr_d} \tag{3.2}$$

Equation (3.3) calculates the remaining transportation cost of delivering biomass from each harvesting area to the fixed plants. It interprets the on-road transportation cost of delivering woody biomass from the forest road-main road junction to the targeted fixed plant, and, is defined by $D_{r_d bu_{p_b}}$(the shortest distance from the high way to the fixed plant that is operating), C_{m_r} (Operational cost of an on-road trailer), and $n_{m_r t}^{r_d bu_{p_b}}$ (required number of on-road trailers to haul the amount of biomass transferred from the tractor-trailers to the on-road trailers).

$$C_2 = \sum_{m_r} \sum_{p_b} \sum_{r_d} D_{r_d bu_{p_b}} . C_{m_r} . n_{m_r t}^{r_d bu_{p_b}} \tag{3.3}$$

The difference between the first and second equation is the selection of a truck able to maneuver on the forest roads and highways. Extensive studies, e.g., Sessions et al. (2010), have provided a comprehensive framework for truck configurations used in the transportation of the forest biomass. In-forest trucks have smaller capacities and greater maneuverability in smaller areas when compared to road trucks (Schroeder et al., 2007). The differences between the in-forest and on-road trucks affect the truck operating costs, and as a result, impact the overall transportation costs, which should not be neglected when assessing the economics of a woody biomass supply chain.

Equation (3.4) calculates the cost of transporting from a mobile plant to a fixed plant and is defined by $D_{p_m p_b}$ (the shortest distance from the mobile plant to the fixed plant), $C_{m_{ta}}$ (Operational cost of a bio-oil tanker), and $n_{m_{ta}t}^{p_m p_b}$ (required number of bio-oil tankers to transport produced bio-oil). In this model, it is assumed that the bio-oil produced by mobile processing plant will be stored in adjacent storage for further processing.

$$C_3=\sum_{p_m}\sum_{p_b}\sum_{m_{ta}} D_{p_m p_b}.C_{m_{ta}}.n_{m_{ta}t}^{p_m p_b} \tag{3.4}$$

Equation (3.5) calculates the transportation cost of delivering woody biomass to the selected location mobile plants and is defined by D_{fp_m} (the shortest distance between harvesting areas and the mobile plant location), C_{m_f} (Operational cost of an in-forest truck), and $n_{m_f t}^{p_m p_b}$ (required number of in-forest trucks to haul the determined amount of woody biomass).

$$C_4 = \sum_{p_m} \sum_{p_b} \sum_{m_f} D_{fp_m}.C_{m_f}.n_{m_f t}^{fp_m} \tag{3.5}$$

Equations (3.6) through (3.9) calculate the cost of establishing one unit of fixed plant, biomass and bio-oil storage facilities attached to the fixed plant, and one unit of mobile plant, and is defined by C_{p_b}, $C_{bu_{p_b}}$, $C_{s_{p_b}}^{bio\text{-}oil}$, C_{p_m}, which are fixed plant capital and operation costs, biomass storage cost, bio-oil storage cost and mobile plant capital and operation costs, respectively. The binary variables φ_{p_b} and τ_{p_m} respectively specify whether a fixed or mobile plant is working. Operation costs primarily consist of electricity, grinding, chemical supplies, and natural gas, which will vary due to the specific size of the plant.

$$C_5 = \sum_{p_b} \varphi_{p_b}.C_{p_b} \tag{3.6}$$

$$C_6 = \sum_{p_b} \varphi_{p_b}.C_{bu_{p_b}} \tag{3.7}$$

$$C_7 = \sum_{p_b} \varphi_{p_b}.\ C_{s_{p_b}}^{bio\text{-}oil} \tag{3.8}$$

$$C_8 = \sum_{p_m} \tau_{p_m}.C_{p_m} \tag{3.9}$$

Equation (3.10) expresses the inventory cost of storing biomass in the storage at the fixed plant and is defined by $C_{I_{bu_{p_b}}}$ (inventory cost of storing woody biomass) and $I_{bu_{p_b}}$(the amount of woody biomass that will be stored)

$$C_9 = \sum_t \sum_{bu_{p_b}} C_{I_{bu_{p_b}}} \,.\, I_{bu_{p_b}t} \tag{3.10}$$

Considering all of the above cost elements, the objective function, Z, to be minimized is presented in Eq. (3.11). Loading and unloading costs are not included in this function since their effect is assumed to be insignificant on the overall cost. Also, as the processing technology is same for both of the plants, the cost related to the fast pyrolysis process is not considered as an effective factor compared to the other terms in the optimization model since this cost is same for both mobile and fixed plant

$$\text{Min } Z = \sum_{m_f} \sum_{p_b} \sum_f D_{fr_d}.C_{m_f}.n_{m_f t}^{fr_d} + \sum_{m_r} \sum_{p_b} \sum_{r_d} D_{r_d bu_{p_b}}.C_{m_r}.n_{m_r t}^{r_d bu_{p_b}} +$$

$$\sum_{p_m} \sum_{p_b} \sum_{m_{ta}} D_{p_m p_b}.C_{m_{ta}}.n_{m_{ta} t}^{p_m p_b} + \sum_{p_m} \sum_{p_b} \sum_{m_f} D_{fp_m}.C_{m_f}.n_{m_f t}^{fp_m} + \sum_{p_b} \varphi_{p_b}.C_{p_b} +$$

$$\sum_{p_b} \varphi_{p_b}.C_{bu_{p_b}} + \sum_{p_b} \varphi_{p_b}.\, C_{s_{p_b}}^{bio\text{-}oil} + \sum_{p_m} \tau_{p_m}.C_{p_m} + \sum_t \sum_{bu_{p_b}} C_{I_{bu_{p_b}}} \,.\, I_{bu_{p_b}t} \tag{3.11}$$

3.3 Constraint Development

Equations (3.12) through (3.15) ensure that the number of in-forest tractor-trailers ($n_{m_f t}^{fr_d}$ and $n_{m_f t}^{fp_m}$), on-highway tractor-trailers ($n_{m_r t}^{r_d bu_{p_b}}$), and tankers ($n_{m_{ta} t}^{p_m p_b}$) that are involved in the process of transportation, have sufficient capacity to transport the amount of woody biomass and bio-oil. There is no constraint on the available number of trucks and tankers in this model and sufficient transportation resources are assumed at each terminal, e.g., harvesting zones, highways, and mobile plant locations, to start the process of transportation. Each of the minor terms in the equations are defined in the nomenclature section and not reported here for brevity.

$$n_{m_f t}^{fr_d} \geq X_{fbu_{p_b}t} / \omega_{m_f} \text{, for}$$

$$f=1,..,F \text{ , } t=1,\ldots,T \text{ , } r_d=1,\ldots,R_D \text{ , and } bu_{p_b}=bu_1,\ldots,bu_{P_B} \qquad (3.\ 12)$$

$$n_{m_r t}^{r_d bu_{p_b}} \geq X_{fbu_{p_b}t} / \omega_{m_r} \text{, for}$$

$$f=1,..,F \text{ , } t=1,\ldots,T \text{ , } r_d=1,\ldots,R_D \text{ , and } bu_{p_b}=bu_1,\ldots,bu_{P_B} \qquad (3.\ 13)$$

$$n_{m_{ta} t}^{p_m p_b} \geq Y_{p_m p_b t} / \omega_{m_{ta}} \text{, for}$$

$$p_m=p_1,\ldots,P_M \text{ ; } p_b=1,\ldots,P_B \text{ ; and } t=1,\ldots,T \qquad (3.\ 14)$$

$$n_{m_f t}^{fp_m} \geq X_{fp_m t} / \omega_{m_f} \text{, for}$$

$$f=1,\ldots,F\ ;\ \ p_m=1,\ldots,P_M\ ;\ \text{and}\ \ t=1,\ldots,T \qquad (3.15)$$

Equations (3.16) and (3.17) guarantee that only a specific percentage of woody biomass (percentage yield) can be transformed to bio-oil. This yield amount is highly dependent on the level of moisture content of each species. As the moisture content decreases, the percentage of the biomass (percentage yield) transformed to bio-oil will increase.

$$\sum_{p_b} Y_{p_m p_b t} = \%\ \text{Yield}\ .\ \sum_f X_{f p_m t},\ \text{for}$$

$$p_m=1,\ldots,P_M \quad t=1,\ldots,T \qquad (3.16)$$

$$Y_{p_b t} = \%\ \text{Yield}.\ j_{bu_{p_b} p_b t}$$

$$p_b=1,\ldots,P_B \quad t=1,\ldots,T \quad bu_{p_b} = bu_1,\ldots,BU_{P_B} \qquad (3.17)$$

Equation (3.18) ensures that total production of bio-oil, through both mobile ($Y_{p_m p_b t}$) and fixed plants ($Y_{p_b t}$), is equal to the specific percentage of transported woody waste from harvesting areas to mobile plants ($X_{f p_m t}$) and the amount transferred from the biomass buffer (storage) to the fixed plants ($j_{bu_{p_b} p_b t}$). This constraint also determines the portion of output that will be produced by each plant to optimize the flow of biomass and bio-oil in the system.

$$\sum_t \sum_{p_b} Y_{p_b t} + \sum_t \sum_{p_b} \sum_{p_m} Y_{p_m p_b t} = \% \text{ Yield.} \sum_t \sum_{p_b} \sum_{bu_{p_b}} j_{bu_{p_b} p_b t} + \% \text{ Yield.} \sum_t \sum_f \sum_{p_m} X_{f p_m t} \quad (3.18)$$

Equations (3.19) and (3.20) ensure that the flow of woody biomass from a harvesting area to a mobile and fixed plant is only possible when the targeted plant is operating.

$$\sum_t \sum_f X_{fbu_{p_b} t} \leq M.\varphi_{p_b}, \text{ for } p_b = 1, \ldots, P_B \quad (3.19)$$

$$\sum_t \sum_f X_{fp_m t} \leq M.\tau_{p_m}, \text{ for } p_m = 1, \ldots, P_M \quad (3.20)$$

Equation (3.21) ensures that the transportation of bio-oil from a mobile plant to a specific fixed plant is practical when the targeted fixed plant is operating. This constraint also allows bio-oil to be distributed among different fixed plants to optimize the flow of this product in the supply chain.

$$\sum_t \sum_{p_m} Y_{p_m p_b t} \leq M.\ \varphi_{p_b}, \text{ for; } p_b = 1, \ldots, P_B \quad (3.21)$$

Equation (3.22) ensures that inventory cost of biomass will be considered as a cost element in the objective function if corresponding fixed plant is operating.

$$\sum_t I_{bu_{p_b}t} \leq M.\ \varphi_{p_b}$$

$$p_b=1,\ldots, P_B \qquad (3.22)$$

Eq. (3.23) and (3.24) ensure that the amount of woody biomass transferred from different harvesting areas to a mobile plant and from storage to the respective fixed plant is less than the capacity of the targeted plant.

$$\sum_f X_{fp_m t} \leq q_{p_m t}, \text{ for;}$$

$$t=1,..T \text{ and } p_m=1,\ldots,P_M \qquad (3.23)$$

$$j_{bu_{p_b} p_b t} \leq q_{p_b t}, \text{ for;}$$

$$t=1,..,T \text{ and } p_b=1,\ldots,P_B \qquad (3.24)$$

Equation (3.25) ensures that the amount of woody waste that will be stored at the fixed plant site will not exceed the storage capacity.

$$I_{bu_{p_b}t} \leq q_{bu_{p_b}t}\ , \text{ for;}$$

$$t=1,..T \text{ and } p_b=1,\ldots,P_B \qquad (3.25)$$

Equation (3.26) determines the amount of woody waste stored during specific period of time. The amount that will be stored in the buffer is dependent on the amount of biomass that is transported from the harvesting areas to the storage and the amount that is shifted from the storage facility to the attached fixed plant for transforming process.

$$I_{bu_{p_b}t} = I_{bu_{p_b}t-1} + \sum_f X_{fbu_{p_b}t} - j_{bu_{p_b}p_b t} \text{ , for;}$$

$$t=1,\ldots,T \text{ , } p_b=1,\ldots,P_B \text{ , and } f=1,\ldots,F \qquad (3.26)$$

Equation (3.27) ensures that the available amount of woody waste in each harvesting area will be either transferred to fixed plants or mobile plants. The existence of this constraint will support the assumption that all of woody waste in the harvesting areas should be converted to bio-oil.

$$\sum_t \sum_{p_m} X_{fp_m t} + \sum_t \sum_{p_b} X_{fbu_{p_b}t} = \partial_f \text{, for;}$$

$$f=1,\ldots,F \qquad (3.27)$$

Equations (3.28-3.29), (3.30), and (3.31) are the binary constraints, integer constraint, and non-negativity constraint, respectively, applied to ensure the solution is feasible.

$$\tau_{p_m} \begin{cases} 1 & \text{if mobile plant is working,} \\ 0 & \text{otherwise} \end{cases} \qquad (3.28)$$

$$\varphi_{p_b} \begin{cases} 1 & \text{if fixed plant is operating,} \\ 0 & \text{otherwise} \end{cases} \tag{3.29}$$

$$n_{m_r t}^{r_d bu_{p_b}},\ n_{m_f t}^{f\, r_d},\ n_{m_f t}^{f\, p_m},\ \text{and}\ n_{m_{ta} t}^{p_m\, p_b}\ \text{are integers} \tag{3.30}$$

$$X_{fp_m t},\ X_{fp_b t},\ I_{bu_{p_b} t},\ j_{bu_{p_b} p_b t},\ Y_{p_m p_b t},\ \text{and}\ Y_{p_b t} \geq 0 \tag{3.31}$$

In this chapter, the objective function and constraints required to develop an optimal combination and number of fixed and mobile plant in the woody biomass supply chain have been explained. The next chapter will focus on applying this approach to the real case in the specific region in Northwest Oregon to assess the validity of this model to optimize bio-oil supply chain costs through a scenario analysis. In addition, the resulting supply chains are evaluated in terms of their relative environmental impacts by assessing the carbon footprint, which is a key indicator for bio-based supply chains.

Chapter 4 - Application of the Approach

Chapter 3 presented a general mathematical model to develop an optimal combination (number and location) of fixed and mobile bio-oil plants in the woody biomass supply chain. In this chapter, a hypothetical case for woody waste to bio-oil processing is presented for a region of northwest Oregon by using actual harvesting data and information available in the literature.

4.1 Application Background and Assumptions

For this study, data for woody biomass amounts and harvesting area locations have been provided by the Oregon Department of Forestry (ODF). The ODF manages a little over 332,000 hectares (821,000 acres) of forestlands in Oregon, which are mostly concentrated in six large state forests and a number of smaller forest areas that are mostly scattered in western Oregon's Coast Range (ODF, 2013). Timber sale harvest data (merchantable and non-merchantable product), the harvesting area GIS layer, and the in-forest and highway road GIS layer for 49 harvesting areas in Astoria, Tillamook, and Forest Grove districts are obtained from the ODF. The Bureau of Land Management (BLM) provides GIS layers containing spatial information about counties in the state of Oregon (BLM, 2013)

4.1.2 Harvesting Areas and Woody Waste Mass

Non-merchantable products are defined as defective timber products that lack sufficient quality to be used for saw logs. However, non-merchantable products can be sold as secondary products and are quite valuable if the market conditions are right, thus, they cannot always be considered as waste.

The amount of non-merchantable products remaining after timbering processes in the previously mentioned three forest zones is considered an input for woody waste in this study. According to an internal report provided by ODF, red alder, western hemlock, and Douglas fir tree species have been primarily harvested for timber in each harvesting area. Appendices 4.1-4.3 report the amount of non-merchantable product for each harvesting project in the three forest zones, i.e., Forest Grove, Tillamook, and Astoria, respectively. For the sake of simplicity and due to a lack of data, it was assumed that the moisture content for all woody waste produced from different harvesting areas is constant (45%).

4.1.3 Bio-oil Processing Plant Locations and Attributes

Since there are currently no bio-oil plants operating in Oregon, the location of fixed plant is assumed for this application. The available 49 harvesting areas are scattered across Tillamook, Clatsop, Columbia, and Washington counties, as shown in Figure 4-1. Hence, it was decided to select the initial locations of the fixed processing plants as the center of each county (Figure 4-2).

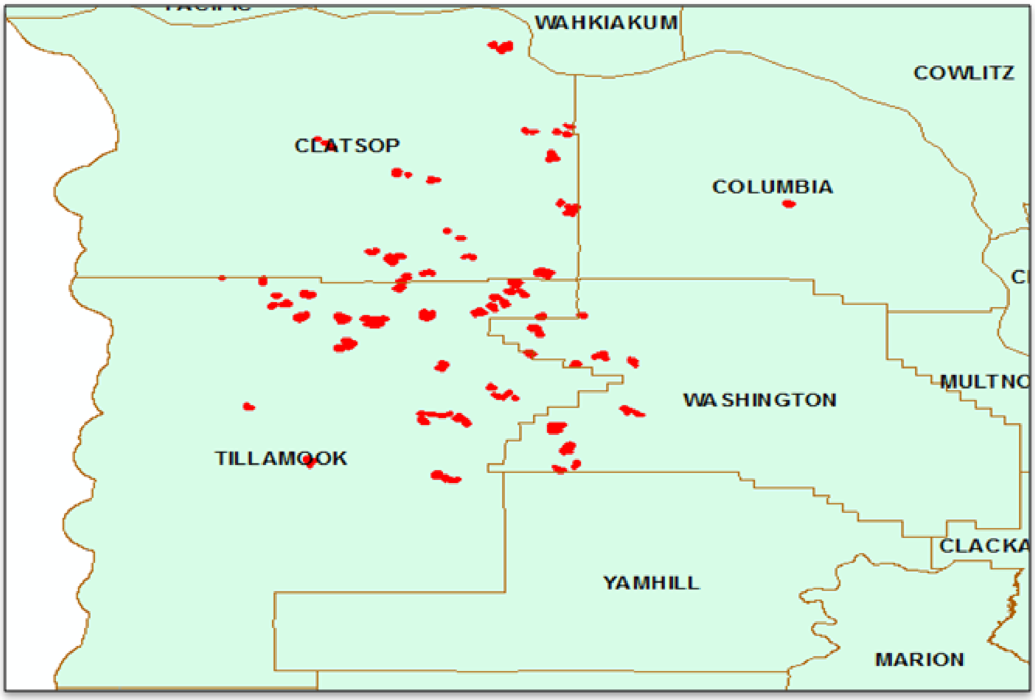

Figure 4-1 Location of 49 harvesting areas in four Oregon counties

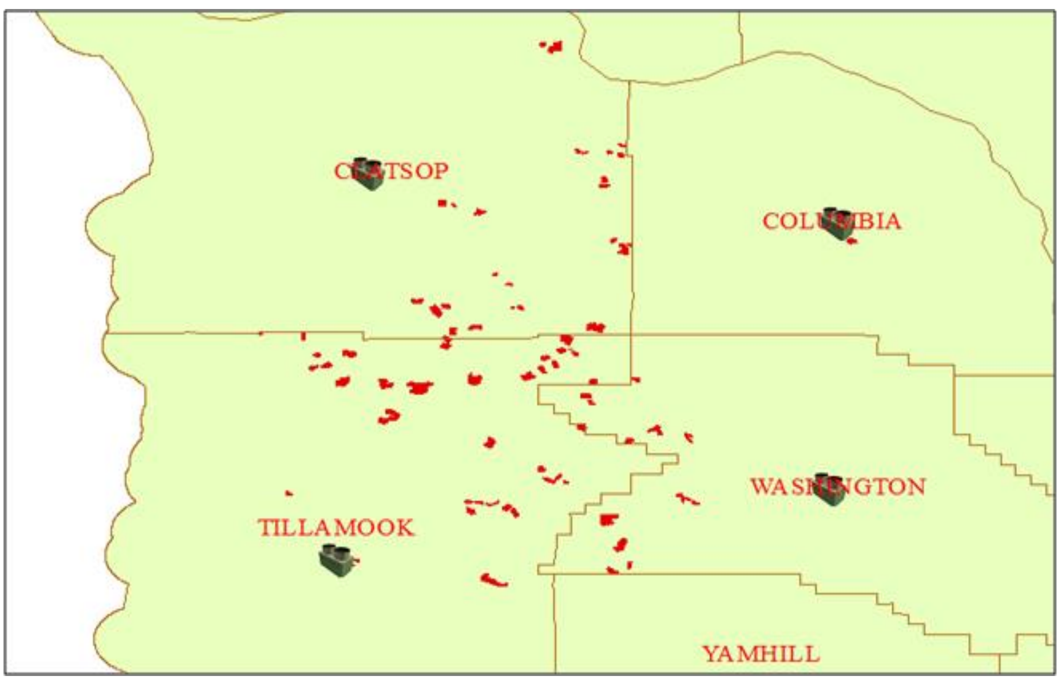

Figure 4-2 Location of assumed fixed plants

The potential locations for mobile plants can be determined based on the geographical distribution of harvesting areas within the three forest zones. Therefore, it is assumed that one mobile plant is located among the geographically closest harvesting projects. In this application, with regard to the geographical locations of available harvesting areas, 16 candidate locations for the settling of mobile plants are determined. Figure 4-3 illustrates an example of placing two mobile plants able to process the amount of woody waste from seven harvesting areas. It should be noted that road layouts were considered in selecting the locations, thus they are not necessarily centrally located with respect to harvesting areas.

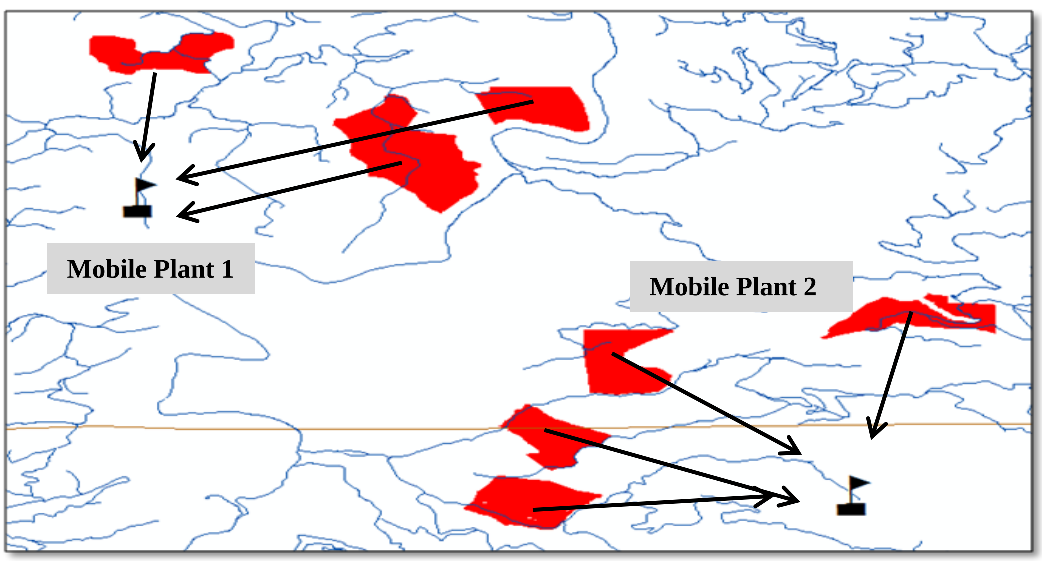

Figure 4-3 Two candidates for mobile plant location and respective harvesting areas

Appendix 4.4 reports the distribution of the 16 mobile plants among the harvesting areas located in three forest districts. It also reports the distance between the harvesting areas to the respective mobile plant and the total amount of woody waste that needs to be processed by each of the 16 mobile plant candidates.

Since the time horizon applied in this application is one year, the capital and operational costs of mobile and fixed plants considered in the mathematical model are highly dependent on two main factors: 1) the expected plant operational life and 2) the period of plant operation in a specific location. The latter factor is more applicable for the mobile plant rather than the fixed plant due to its transportable nature. According to Dumroese et al. (2009) the expected life for a mobile processing unit is 10 years, and for the sake of simplicity, this same time period has been considered for fixed plants.

Mobile plant capacity and capital and operational costs have been calculated respective to the data reported by Farag et al. (2001) and Dumroese et al. (2009). The same information for fixed plants has been extracted from a report developed by Farang et al. (2001). Attributes of both types of plants that are considered in this application have been summarized in Table 4-1.

Table 4-1 Summary of mobile and fixed plant attributes

Attributes	Mobile Plant	Fixed Plant
Plant size (tons per day)	15	400
Wood (45% MC) processing rate (tons per year)	5,456	145,505
Bio-oil production capacity (gallons per year)	435,148	11,603,945
Capital cost ($)	1,472,000	14,300,000
Operational cost ($ per year)	182,340	3,052,272
Biomass storage cost ($ per year)	-	678,240
Bio-oil storage cost ($ per year)	-	1,408,823
Expected operational life (year)	10	10
Bio-oil product yield (%)	33.5	33.5

The operational cost for the fixed plant was obtained from the report by Farag et al. (2001), and for the mobile plant was estimated using the empirical model shown in Eq. (4.1), which is based on a linear interpolation of operational cost (Y) for different sizes (ton per day) of fixed plants (X). Operational cost includes electricity, chemical supplies, natural gas, and grinding cost of the process.

$$Y=7454.2\ X+70527 \tag{4.1}$$

The cost related to different types of storage has been analyzed by Rentizelas et al. (2009) and has been discussed in Chapter 2. The biomass storage facility assumed in this application is a covered warehouse without drying infrastructure, which has an associated capital cost of $144/m^2. One cubic shaped biomass storage facility with a height of 6m and width and length of 28m is assumed in this application. The flow of woody biomass from harvesting areas to the fixed plant has been assumed as just-in-time and no inventory cost is considered for this application. In other words, it assumed that the processing activity of woody waste will be started as soon as the batches of woody waste arrive at the fixed plants instead of storing feedstock.

To model the cost of bio-oil storage at the fixed plant, two steel tanks with a capacity of 105,618 metric drums (180000 bbl), each, and capital cost of approximately $1.4M, each, are selected (B2-Consultants, 2013). Since the mobile plant has the ability to relocate in the forest to serve different harvesting areas, there is no need to consider biomass and bio-oil storage for this type of processing plant.

The annual cost, i.e., capital and operational costs, of a fixed plant is calculated using Eq. (4.2) which assumes straight line amortization, with k representing the expected operational life. As stated earlier, the expected operational life for the plants in this application is assumed to be 10 years. The total annual mobile plant cost, i.e., operational and amortized capital cost of each mobile plant operating in a given location is calculated using Eq. (4.3), which assumes that the mobile plant will be moved to a new harvest area as soon as woody biomass in the current area is processed; it is unlikely that a mobile plant will be in one location for an entire year.

$$C_{p_b} = {}^{\text{Total } C_{p_b}}\!/_{k} \text{ , for; } p_b = 1, \ldots, P_B \qquad (4.2)$$

$$C_{p_m} = {}^{\text{Total } C_{p_m}}\!/_{k} \cdot {}^{\sum_f X_{f p_m t}}\!/_{q_{p_m t}} \text{ , for; } t=1 \text{ and } p_m = 1, \ldots, P_M \qquad (4.3)$$

4.1.4 Distance Calculation

A road network was developed in GIS software (ArcGIS 10) to calculate the travel distance between two locations. The road GIS layer provides two main categories for road types, forest roads and highways. With regard to the structure of the map, all forest roads feed into highways. The shortest paths between harvesting areas and fixed plants, considering both forest roads and highways, and between the mobile plants and fixed plants, are reported in Appendices 4.5-4.12. The distances between harvesting areas and corresponding mobile plants is reported in Appendix 4.4.

Figure 4-4 depicts the path, including forest roads and highways, between one harvesting area and the fixed plant located in Tillamook County. It can be seen that the road does not reach the fixed plant, however, this distance can be neglected as it is insignificant compared to the total path length.

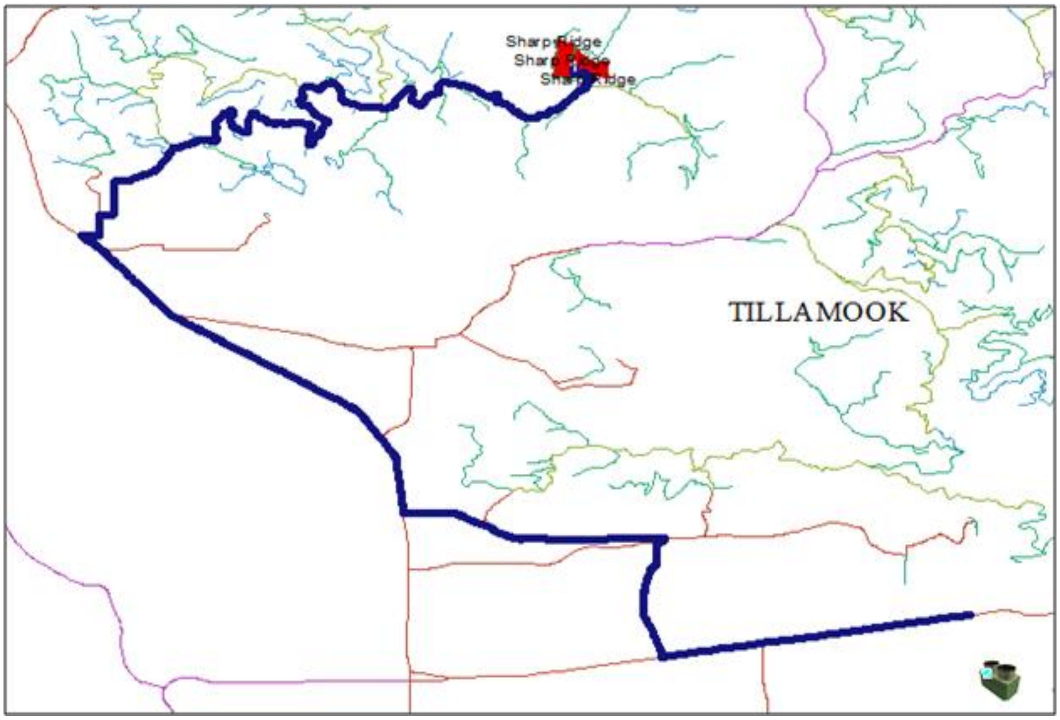

Figure 4-4 Shortest path between the Sharp Ridge harvesting area and the fixed bio-oil processing plant located in Tillamook county

4.1.5 Truck Operating Cost

Different truck types will have different operating ratios (cost per mile) since they will maneuver in different terrains. Barnes and Langthworthy (2003) analyzed the operating costs of automobiles and trucks, which reflect lower fuel costs a decade ago than today. By adjusting these estimates for inflation, the operating ratio of driving a truck on a smooth highway, considering cost of tires, maintenance, depreciation and average fuel cost in 2012 is calculated as $0.89, while for extremely poor pavement it is estimated as $0.81. Table 4-2 illustrates the cost related to each type of truck used in this study. The operating ratio for the bio-oil tanker is assumed to be the average cost of smooth pathway and poor pavement road conditions, since it will operate on both types of roads. Table 4-3 illustrates the attributes of selected trucks in this application.

Table 4-2 Operating ratio for each type truck

Type of Truck	**Operating Ratio ($ per mile)**
In-forest tractor trailer	0.89
On-highway tractor trailer	0.81
Tanker truck	0.85

Table 4-3 Truck attributes

Truck	**Gross Weight (US tons)**	**Typical Payload (US tons)**
In-forest tractor trailer	14.75	9.25
On-highway tractor trailer	28.25	20.00
Tanker truck	14.75	9.25

4.2 Computational Results

The optimization model presented in Chapter 3 (Equations 3.11-3.31) is solved using an integer programming solver (CPLEX 12.5). The model has 619 constraints, 20 binary variables, 506 integer variables, and 318 non-negative variables. For this case, which assumes 16 potential mobile plant locations and four potential fixed plant locations, the results indicate that the optimal supply chain would consist of one fixed and one mobile plant, for an annual cost of

$4,889,067 when considering transportation costs and the capital costs of each plant. Figure 4.5 displays a portion of the map illustrating the location of mobile and fixed plants for the optimal solution. Appendix 4.13 displays the full view of the map showing the location of the mobile and fixed plants and all of the harvesting areas.

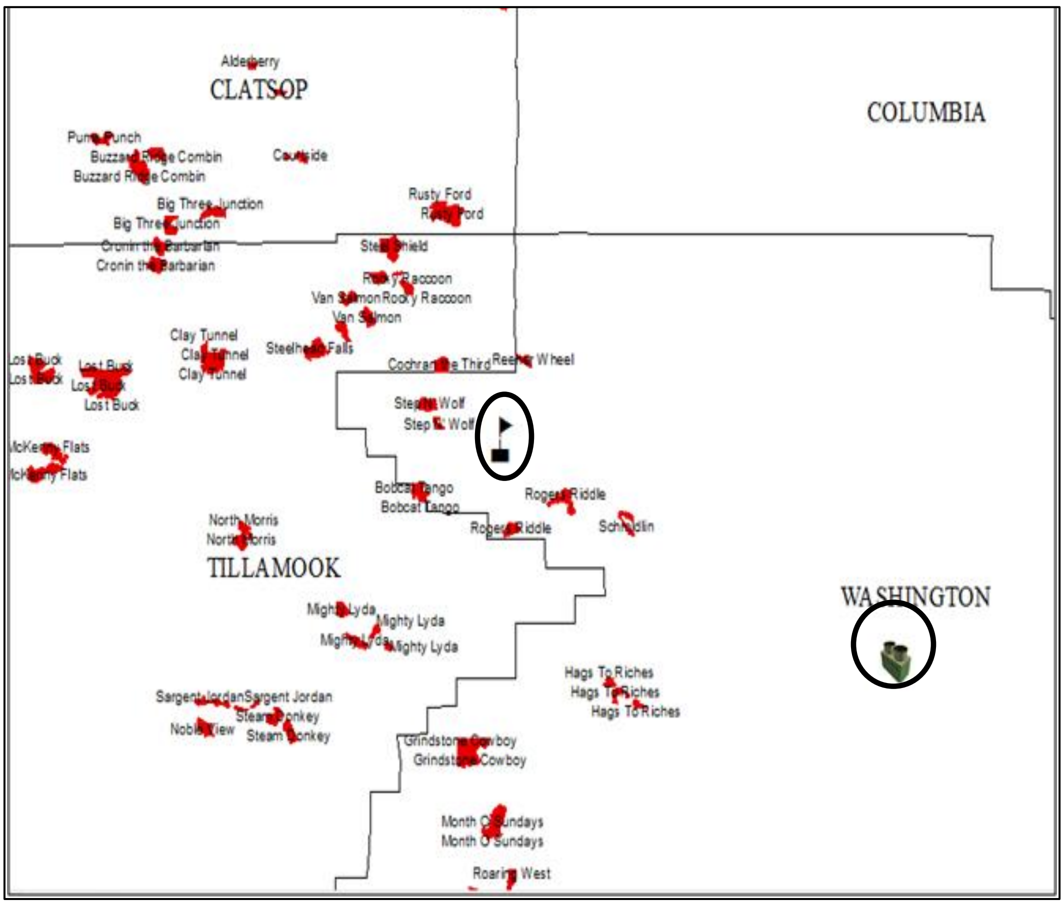

Figure 4-5 Portion of understudy map depicting the optimal location of mobile and fixed plants

The optimal location for mobile plant placement is among four harvesting areas, i.e., Reeher Wheel and Step N' Wolf in Washington County, and Bobcat Tango and Cochran the Third in Tillamook County, that will process a partial amount of woody biomass available in these harvesting areas. The remaining of woody waste will be processed by the fixed plant located in the center of Washington County. The optimal division of woody waste between fixed and mobile plants leads to the total production of about 4253 US tons of bio-oil. Table 4-4 illustrates the details for the optimal solution of the mathematical model applied in this case study.

Table 4-4 Values for selected model parameters for the optimized supply chain

Parameter Description	**Parameter Name**	**Parameter Value**
Woody waste transferred to the mobile plant (US tons)	X_{fp_mt}	156.25
Woody waste transferred to the fixed plant in (US tons)	X_{fp_bt}	12540.88
Number of in-forest trucks	$n_{m_ft}^{f\,r_d}$ and $n_{m_ft}^{f\,p_m}$	1399
Number of highway trucks	$n_{m_rt}^{r_dbu_{p_b}}$	652
Number of bio-oil tankers	$n_{m_{ta}t}^{p_m\,p_b}$	6
Bio-oil produced by the mobile plant (US tons)	$Y_{p_mp_bt}$	52.34
Bio-oil produced by the fixed plant (US tons)	Y_{p_bt}	4201.19

Regarding the performance of the mathematical model, CPLEX solves the problem to optimality after 1166 iterations and 0.61 seconds.

4.3 Environmental Impact Assessment

The environmental impact assessment method applied in this case study focuses on estimating the carbon footprint (measured using kg CO_2 equivalent) of the transportation activities and bio-refinery plants. CO_2 equivalent is a unit to measure carbon footprint by expressing the impact of each greenhouse gas, e.g., methane, carbon dioxide, and nitrous oxide, in terms of the amount CO_2 that could have an equivalent level of global warming potential. According to a report released by U.S. Environmental Protection Agency, the carbon footprint for heavy- and medium- duty trucks is 1.73 kg CO_2 eq. per ton-mile (U.S. EPA, 2008). Due to the fact that transforming woody biomass to bio-oil at a bio-refinery plant is a novel approach, there is a dearth of literature focusing on assessing the environmental impact of this process, and especially so for the environmental impact of establishing a bio-refinery plant. To assess the impact of the construction of this type of plants on the environment, it is modeled as ethanol fermentation plant using SimaPro 7, a widely used life cycle assessment software tool.

The carbon footprint of the plant infrastructure is calculated as 5,350 tons of CO_2 equivalent, including fuel transformation process, use of materials, energy uses, emissions, and dismantling, for an annual capacity of 90,000 tons of ethanol. Converting the amount of ethanol to bio-oil by multiplying the amount ethanol output by the energy density ratio and then dividing the CO_2 equivalent value by the expected operational life of 20 years, the annual CO_2 equivalent emissions for a selected bio-oil refinery can be obtained. Table 4-5 reports the estimated carbon footprint for the understudy fixed and mobile plants and transportation activities.

Table 4-5 Environmental impact of plants and transportation activity used in the case study

Supply Chain Entity	Carbon Footprint (kg CO_2 eq.)
Fixed plant (400 tpd)	2,623,548
Mobile plant (15 tpd)	98,383.08
Transportation (per ton-mile)	2,721,932.02
Total carbon footprint (kg CO_2 eq.)	**3,661,498.87**

4.4 Sensitivity Analysis

With regard to the structure of the optimization model developed in Chapter 2, several factors can have a crucial effect on the environmental impact, overall cost of the system, and optimal number and location of fixed and mobile plants. The purpose of the sensitivity analysis performed is to assess the effect of six major factors, explained below, on the economic and environmental results obtained in this case study.

Two cases, in addition to the baseline case developed in sections 4.2 and 4.3, have been considered for each factor and the environmental impact and annual cost of cases have been compared factor by factor.

4.4.1 Effect of Mobile Plant Capital Cost

The effect of the annual cost of a mobile plant, by changing the capital cost and expected operational life of the plant, is investigated in this section. In the baseline case the capital cost of one unit of mobile plant was about $1.47 million with the expected operational life of 10 years.

In the first alternative scenario (Case 1), the capital cost of a mobile plant has been decreased by 50%, and in the second case (Case 2), in addition to the reduction in the capital cost, the assumed operational life of the plant has been increased to 20 years. These cases reflect expected technology improvements. All other model parameters remained the same as the baseline scenario. Table 4-6 reports the overall cost and carbon footprint corresponding to each case.

Table 4-6 Effect of mobile plant capital cost on overall annual cost and carbon footprint

Scenario	Overall Annual Cost ($)	Total Carbon Footprint (in kg CO_2 eq.)
Base Case	4,889,067.24	3,661,498.87
Case 1	4,883,384.12	3,661,498.87
Case 2	4,880,528.48	4,167,201.51

According to the results, the optimal number and location of the fixed and mobile plants remain the same for these two cases comparing to the baseline case. The amount of woody waste that should be processed through the selected mobile plant remained constant for Case 1, however, this variable has increased from

156.25 tons to 162.10 tons when the expected operational life of the plant increased and the capital cost of the mobile plant decreased simultaneously. The overall cost is decreased by about $6,000 (0.12%), in Case 1, and by about $9,000 (0.17%) in Case 2. The carbon footprint remains constant in Case 1 while it is increased by about 557 tons of CO_2 eq. since more woody waste will be processed by the selected mobile plant. Figure 4-6 shows the comparison of economic and environmental impacts among these three scenarios.

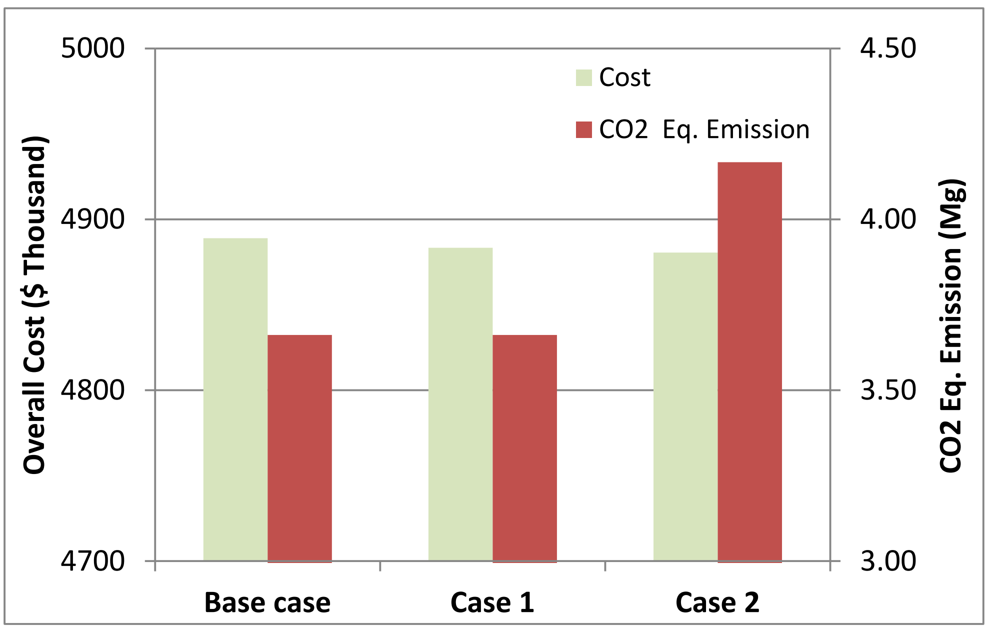

Figure 4-6 Effect of mobile plant capital cost on overall annual cost and carbon footprint

The analysis reveals that capital cost, as one of the major cost elements in the model, has an impact on the optimal solution. As capital cost of the mobile plant decreases, more amount of woody waste will be processed by the selected plant and the role of mobile plant becomes more apparent.

4.4.2 Effect of Mobile Plant Operational Cost

Since little information about the operational cost of a mobile plant was attainable in previous literature, this cost was estimated through an empirical model explained in Section 4.1.2. In order to investigate the impact of operational cost on the optimal number and location of mobile and fixed plants, two scenarios in addition to the base case, were developed in which only the operational cost of a mobile plant has been varied.

In the first scenario (Case 3), an increase of 20% in operational cost has been considered in calculating the total cost of the mobile plant, and in the second scenario (Case 4), a 20% reduction in operational cost was assumed. Table 4-7 reports the overall cost and carbon footprint corresponding to each case.

Table 4-7 Effect of the mobile plant operational cost on the overall annual cost and carbon footprint

Scenario	Overall Cost ($)	Total Carbon Footprint (kg CO_2 eq.)
Base Case	4,889,067.24	3,661,498.87
Case 3	4,891,885.76	3,661,498.87
Case 4	4,886,249.34	3,661,498.87

The optimal number and location of fixed and mobile plants, and subsequently, the amount of CO_2 emissions, remain constant for Case 3 and Case 4. The annual cost is directly dependent on the operational cost of the mobile plant, hence the annual cost in Case 3 is increased by about $2,800 (0.05%) and the annual cost in

Case 4 is reduced by $2,800 (0.05%). These results are shown graphically in Figure 4.7.

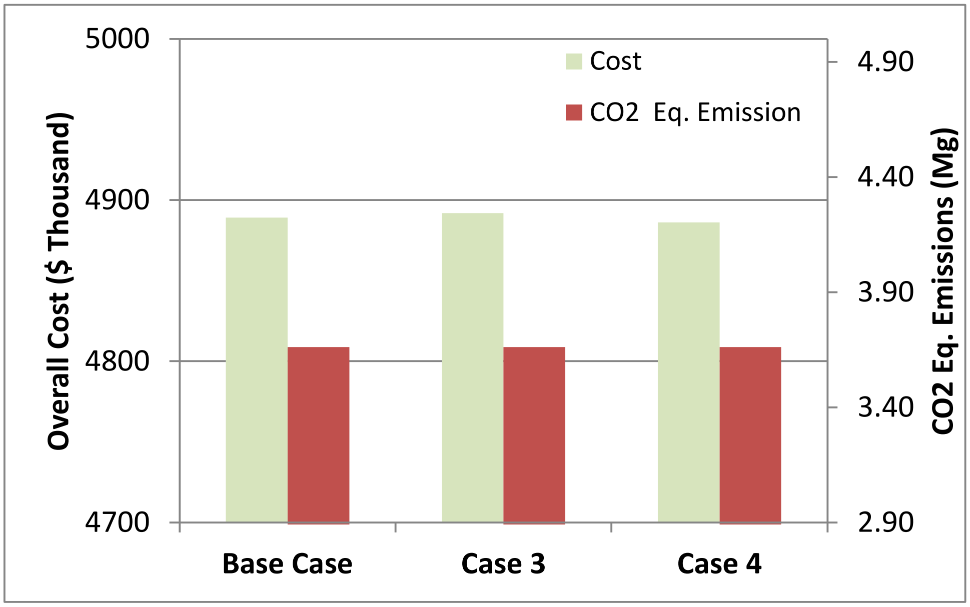

Figure 4-7-Effect of operational cost of mobile plant on overall annual cost and carbon footprint

The results show that change in the operational cost of mobile plant does not impact on the optimal combination of fixed and mobile plants, nor does it impact the supply chain configuration.

4.4.3 Effect of Fixed Plant Locations

The effect of distance, as the primary factor in determining the location and number of fixed and mobile plants, was next investigated. In the baseline scenario, the fixed plant locations were assumed to be at the center of counties.

In the first alternative scenario (Case 5), fixed plants were located at a distance of 300 miles farther from their original locations, and in the second case (Case 6) they were placed at a distance of 1200 mile from the original locations. All other model parameters remained the same as the baseline scenario.

According to the results, the optimal number and location of the fixed and mobile plants remain the same for these two cases compared to the base case. The amount of woody waste that should be processed through the selected mobile plant, however, has increased as the distance increases and more harvesting areas are served by the selected mobile plants.

The amount of woody waste that will be processed by the selected mobile plant in Case 5 and Case 6 is increased from 156.25 tons, in baseline case, to 271.11 tons. As shown in Table 4-8, as distance increases, the overall annual cost and carbon footprint increase.

Table 4-8 Effect of fixed plant location on the overall annual cost and carbon footprint

Scenario	Overall Annual Cost ($)	Total Carbon Footprint (kg CO_2 eq.)
Base Case	4,889,067.24	3,661,498.87
Case 5	5,048,420.34	28,972,110.42
Case 6	5,526,275.34	41,993,629.27

The overall annual cost and carbon footprint increased directly due to an increase in transportation activity. The overall cost in Case 5 is increased by about $156,000 (3.1%) and carbon footprint is increased by 27,900 tons (691%). The annual cost in Case 6 is increased by about $637,000 (13%) and carbon footprint is increased by 42,253 tons (1046%). Figure 4.8 shows the comparison of economic and environmental impacts among these three scenarios.

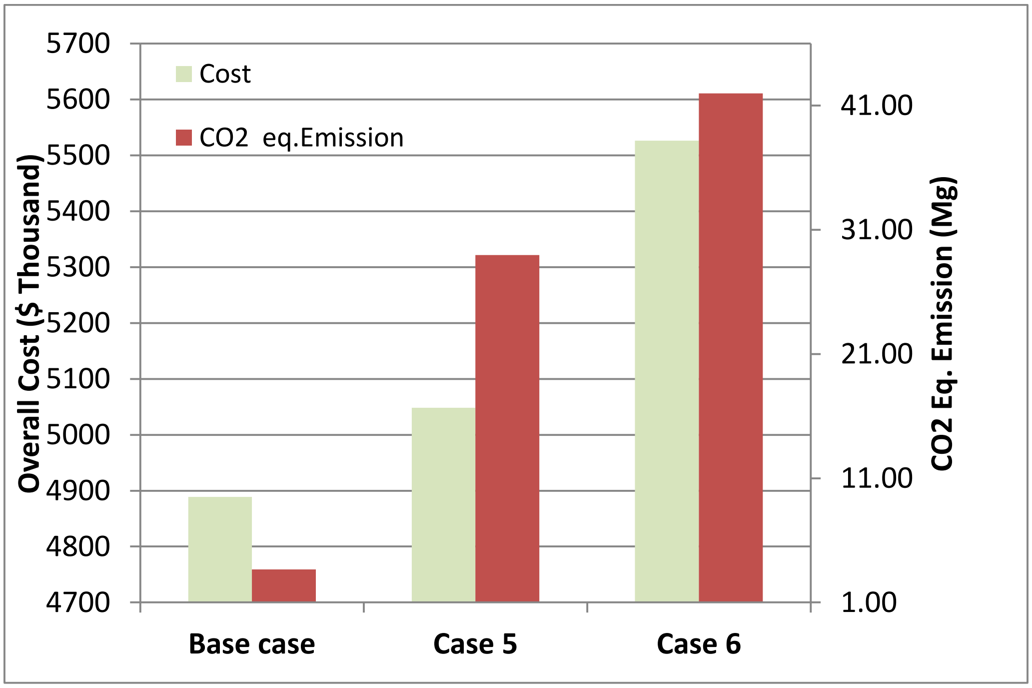

Figure 4-8 Effect of fixed plant location on overall annual cost and carbon footprint

The results show that more woody waste will be processed by the selected mobile plant as transportation distance to the fixed plant increases.

4.4.4 Effect of Available Woody Biomass

As stated above, the amount of woody waste considered in the baseline scenario was obtained from an ODF internal report. This amount was based on non-merchantable products remaining after timbering in three forest districts. However, this type of woody waste would not be the sole source for a bio-oil supply chain. The leftover slash, which would be burned on state and privately owned forests, can be considered as another source of woody waste. Roughly 2,500 to 3,000 tons per year- per forest of slash are intended to be burned by ODF as no market exists for this type of waste. The amount of slash is greater for private ownerships, since they harvest a larger area, equating to about 12,500-13,000 tons for each forest zone, i.e., Tillamook, Astoria, and Forest Grove.

In the first case (Case 7), the amount of leftover slash corresponding to that available in the state forests has been added to the total amount of woody waste in the original scenario, while the other parameters remain constant. It is assumed that 9,000 tons of leftover slash, or 3,000 tons per forest, are distributed normally among 49 harvesting areas. In the second case (Case 8), the leftover amount from the private owned forests (approximately 37,500 tons, or 12,500 per forest zone) has been added to the first case (Case 7) assuming that it is distributed evenly across the 49 harvesting areas.

The analysis found that no mobile plants would be used in Case 7 and Case 8, and all of the woody waste would be processed through one fixed plant located in Washington County. As the amount of available woody waste increases, the number of trips and transportation will increase. To minimize the overall cost, the solver would decide to eliminate the role of a mobile plant while considering the total cost of a mobile plant and accept the high transportation cost which is due to an increase in the number of travels. Table 4-9 reports the overall cost and Carbon footprint corresponding to each case.

Table 4-9 Effect of available amount of woody waste on the overall annual cost and carbon footprint

Scenario	Overall Annual Cost ($)	Total Carbon Footprint (kg CO_2 eq.)
Base Case	4,889,067.24	3,661,498.87
Case 7	4,883,633.3	6,128,049.08
Case 8	4,967,255.08	12,190,934.81

The annual cost is decreased by about $5,000 (0.11%) in Case 7 since no mobile plant is operating and is increased by about $78,000 (1.6%) in Case 8 compared to the base case since number of trips have increased due to large volume of woody waste. The carbon footprint is increased by about 2,718 tons (67.36%) in Case 7 and is increased by 9,402 tons (232.9%) in Case 8 when comparing to the base case. The result of this increase in CO_2 emission is due an increase in transportation activity. Figure 4-9 illustrates how environmental and economic impacts vary among these three scenarios.

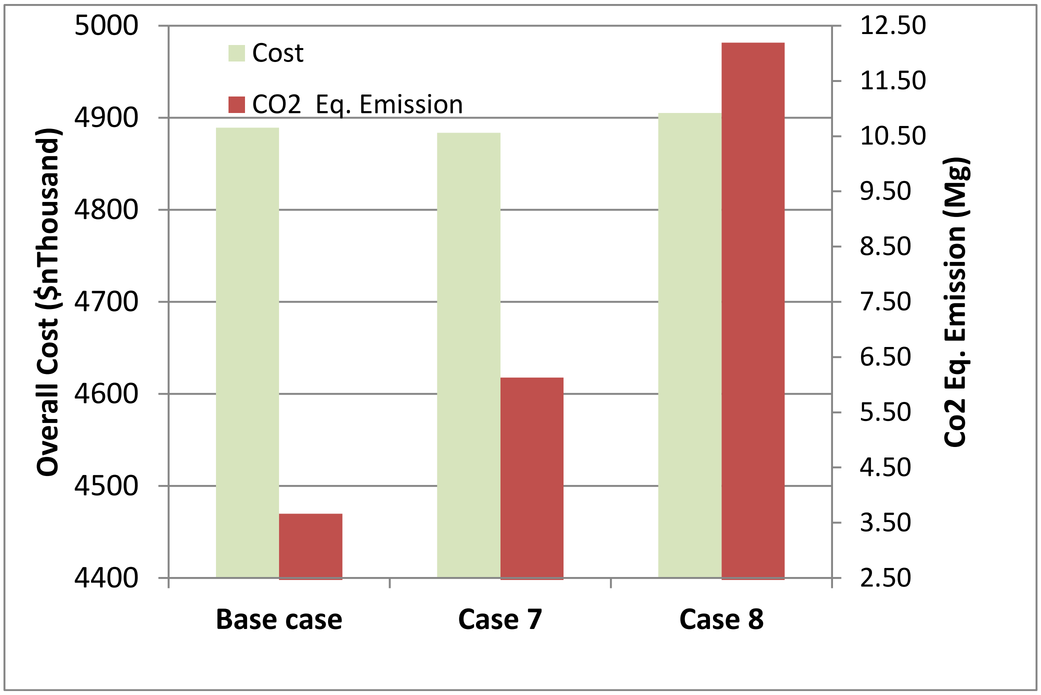

Figure 4-9 Effect of available amount of woody waste on overall annual cost and carbon footprint

The results show that the mathematical model developed in this study is sensitive to capital cost as well as transportation cost. As the transportation activity increases, the model will decide to eliminate the role of mobile plant and process the whole amount of woody waste using the selected fixed plant.

4.4.5 Effect of Truck Operation Cost

Another factor that has been investigated in this sensitivity analysis is the operation costs of the trucks considered. In first scenario (Case 9), the operation cost has been decreased by 50%, holding other parameters constant, and in the second scenario (Case 10) this cost is increased by 50%, holding other parameters constant. The results of these cases show that truck operation cost does not have an effect on the optimal location and number of fixed and mobile plants; and the only factor that is dependent on the operational cost of the truck is the overall system cost. In addition, as the cost of per trip increases, more woody waste will be processed by the selected mobile plant. The amount of woody waste process increases to 180 tons in Case 10, compared to 156.26 tons in the base case and Case 9.Table 4-10 reports the overall cost and the carbon footprint corresponding to each case.

Table 4-10 Effect of truck operation cost on overall annual cost and carbon footprint

Scenario	Overall Annual Cost ($)	Total Carbon Footprint (kg CO_2 eq.)
Base Case	4,889,067.24	3,661,498.87
Case 9	4,873,189.35	3,661,498.87
Case 10	4,904,951.09	4,171,111.64

The overall annual cost is decreased by about $16,000 (0.32%) in Case 9 and increased by about $16,000 (0.32%) in Case 10. Carbon footprint is increased by about 561 tons (19.96%) in Case 10 comparing to the baseline scenario and Case 9. An increase in the overall cost for Case 10 is due to an increase in the transportation cost of the trucks. The increase in carbon footprint is because of an increase in the number of trips due to processing more woody waste from harvesting areas by the selected mobile plant. Figure 4-10 illustrates how environmental and economic impacts vary among these three scenarios.

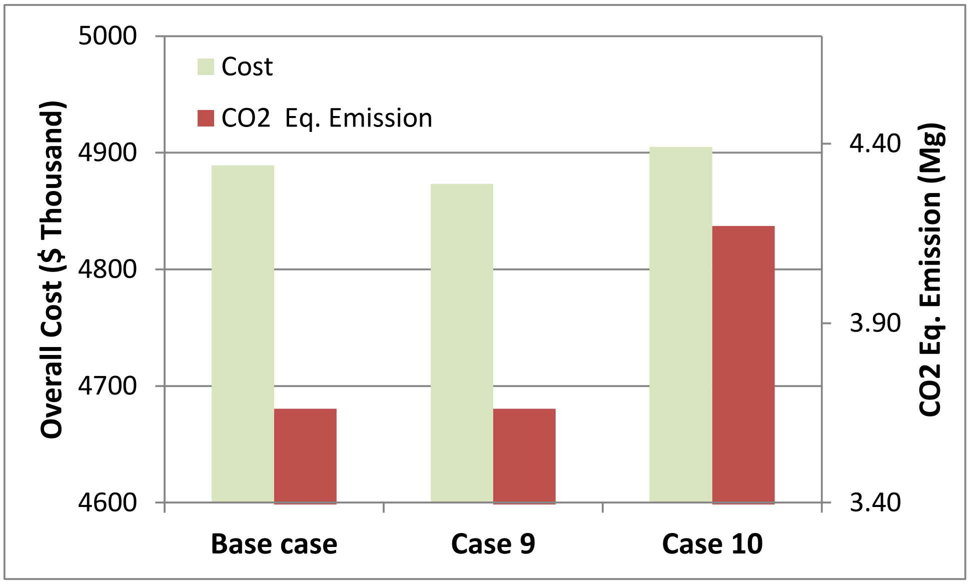

Figure 4-10- Effect of truck transportation cost on overall annual cost and carbon footprint

The results show that the amount of woody waste processed by the selected mobile remained constant in the base case and with lower truck operating cost (Case 9), which leads to same carbon footprint for these two cases. However, as the transportation cost increases, the amount of woody biomass processed through the selected mobile plant increases. Other exploration of the model revealed high truck operating costs would result in eliminating the use of the mobile plant, which is a similar effect as increasing transportation distance.

4.4.6 Effect the Bio-oil and Biomass Storage Costs

The capital costs of bio-oil and biomass storage have been estimated in this application. Two scenarios were developed to analyze the impact of different storage capital costs on overall cost and carbon footprint.

In the first case (Case 11), the costs of constructing bio-oil and biomass storage facilities were decreased by 20%, and in the second case (Case 12), these costs were increased by 20%. The results show no change in the optimal number and location of fixed and mobile plants, the amount of woody waste processed by the selected mobile plant, and the carbon footprint. However, the overall cost changes in relation to the change in bio-oil and biomass storage costs. Table 4-11 reports the overall cost and carbon footprint corresponding to each scenario.

Table 4-11 Effect of bio-oil and biomass storage costs on overall cost and carbon footprint

Scenario	**Overall Annual Cost ($)**	**Total Carbon Footprint (kg CO_2 eq.)**
Base Case	4,889,067.24	3,661498.87
Case 11	4,819,149.5	3,661498.87
Case 12	4,958,881.75	3,661498.87

There is no change in carbon footprint by varying the capital cost of biomass and bio-oil storage, but the overall cost of the system is reduced by about $70,000 (%1.43) in Case 11. It is increased by the same amount in Case 12 compared to the base case. Figure 4-11 illustrates the effect on environmental impact and overall cost for each case.

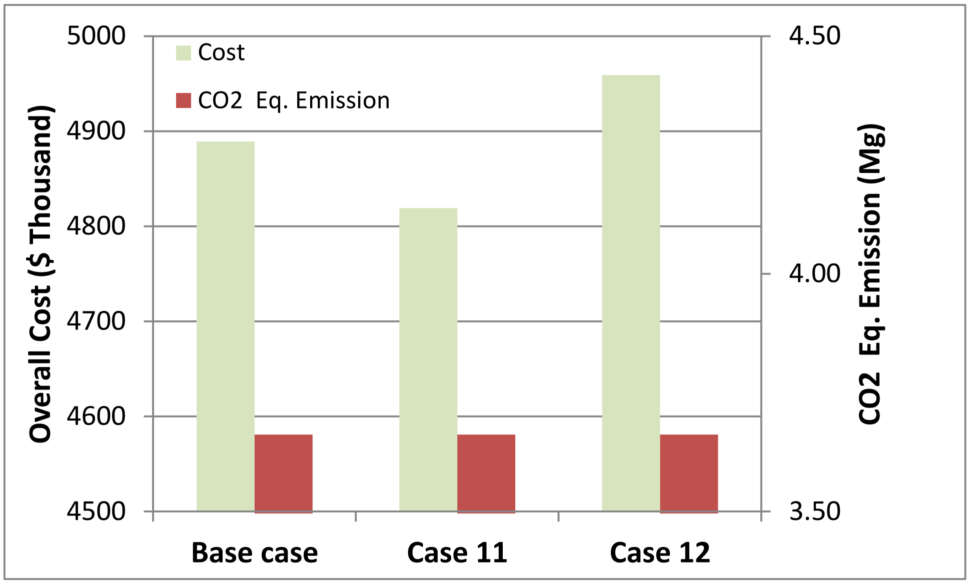

Figure 4-11 Effect of bio-oil and biomass storage costs on overall annual cost and carbon footprint

As it can be seen from the figure, there is no difference in the carbon footprint, while the overall cost varies due to the change in the biomass and bio-oil storage costs. The result shows that the optimal solution is not sensitive to a change in biomass and bio-oil storage costs.

Chapter 5 - Discussion and Conclusions

In this chapter, the summary of the application of the mathematical model developed in Chapter 3 along with sensitivity analysis of six major factors will be discussed. Conclusions based on the work will be drawn in next section. Finally, the contributions of this research are reported and the limitations of the study and future research opportunities are discussed.

5.1 Summary

This thesis has provided an overview of the literature (Chapter 2) and the development of a mathematical model (Chapter 3) for optimizing the number and placement of mobile and fixed processing plants in a woody waste to bio-oil supply chain. In Chapter 4, the proposed mathematical model developed in Chapter 3 was applied to a case in northwest Oregon. Sixteen location candidates for mobile plants and four location candidates for fixed plants were assumed in the study. The actual travel distance between two map locations was calculated using ArcGIS software, and the capital and operational costs of mobile and fixed plants were extracted from previous literature.

The mathematical model was solved using an integer programming solver (CPLEX 12.5), which obtained one location for each type of plant as an optimal result. The selected mobile plant was located among four harvesting areas, and the selected fixed plant was located in the center of Washington County. The amount of woody waste that was assigned to be processed by the mobile plant was 5.96 tons, which was a small fraction of the amount of available woody waste in the four harvesting areas. The remaining mass, i.e., 12,691.18 tons, had been assigned to the fixed plant for transformation into bio-oil. The annual supply chain cost of the base case, considering transportation and overall cost of each plant, was estimated to be $4,873,844.

The environmental impact assessment measured the carbon footprint as the CO_2 equivalent of emissions of transportation activities and the bio-refinery plants. The carbon footprint of the fixed bio-oil refinery was calculated based on the environmental impact of an ethanol fermentation plant, and calculated using SimaPro life cycle assessment (LCA) software. The carbon footprint multiplier for transportation activities was extracted from previous literature. The total carbon footprint for the base case was estimated to be 4,064,535 kg CO_2 eq.

Sensitivity analysis on six factors was performed to evaluate the impact of each factor on the overall cost, the carbon footprint, and the optimal number and location of fixed and mobile plants. Each factor was examined for two different conditions to compare the results with the outcomes obtained for the base case.

The next section will explore more about the effect of each factor investigated on the modeling results.

5.2 Conclusions

The operational cost of the mobile plant and the capital cost of bio-oil and biomass storage at the fixed plants were assumed values in this study. As a result, the impact of these two factors on the result of the base case was investigated by introducing two scenarios. The results of the scenario analysis showed that variation of the mobile plant operational cost and storage facility costs at the fixed plant do not have a significant impact on the number and location of plants, nor do they impact predicted carbon footprint. However, as expected, the overall cost of the system was directly dependent on these cost changes; as the operational cost and capital cost of storage facilities increase, the overall cost of the system increases and vice versa.

Similarly, two cases were developed to investigate the impact of changing the capital cost of mobile plant by decreasing it by %25 in first case and increasing operational life by ten years in the second case. This analysis resulted in the different outcome for the supply chain model. The outcome of decreasing the capital cost of mobile plant didn’t change the optimal solution however, an increase in the operational life of the plant, in addition to the decrease in the capital cost of mobile plant, resulted in an increase in the selected mobile plant utilization.

The fixed plant location was evaluated to examine the effect of distance on cost and carbon footprint. Even though the optimal number and location of plants did not change when varying the location of fixed plants, the amount of woody waste allocated to the selected mobile plant increased dramatically from 156 tons to 271 tons, by placing fixed plants 300 and 1200 miles away from their initial locations. This change in distance was also accompanied by an increase in the overall cost and carbon footprint of the system. The impact of distance on the available input for the mobile plant confirms the hypothesis that distance, and subsequently, transportation, has a great influence on the woody biomass supply chain sustainability performance. As would be expected, due to energy densification, the distance between the harvesting area and distribution centers increases, a greater amount of woody waste should be processed into bio-oil by mobile plants.

To confirm the impact of transportation on bio-oil supply chain decision making, two cases for different truck operational costs were investigated. The analysis revealed that as the operating ratio (cost per mile) of a truck increases, more woody waste would be allocated to a mobile plant for the transformation process. This result again supports the hypothesis that it is preferable to transfer bio-oil rather than biomass due to high transportation costs of low energy density fuel.

The last factor examined in the sensitivity analysis was the amount of available woody waste. Two scenarios were developed to investigate the effect on modeling outputs of an increase in the amount of woody waste by adding the state forest leftover slash to the base case amount, in the first alternative case, and adding private and state forest leftover slash, in the second case. An increase in the volume of woody waste leads to an increase in the number of trips and, subsequently, an increase in transportation cost. When considering the overall cost of a mobile plant accompanied by an increase in transportation cost, the solver decided to eliminate the use of a mobile plant. This choice showed that it is in the benefit of decision makers to process the entire amount of woody waste in the fixed plant located in Washington County. This conclusion is counter to intuition due to limitations of the current distance determination approach, as described in Section 5.4.

5.3 Contributions

The results gained from developing and applying the mathematical model in the case study, and from undertaking sensitivity analyses of key modeling assumptions, facilitated answering the research question proposed in Chapter 1: Is the combination of fixed and mobile plants in the woody biomass to bio-oil supply chain cost efficient? This thesis is the first reported work to explore this question.

The impact of transportation activities, e.g., an increase in distance and a change in the operation cost of the trucks, highlights the potentially positive impact of the mobile plant on the overall cost of woody biomass supply chain. As it was examined through investigating several cases in the sensitivity analysis section, a greater volume of biomass will be processed by a mobile plant if the location of distribution centers is farther away from the harvesting area or if the transportation cost increases.

As a result, from the economic view point, if bio-oil developers are experiencing expensive truck costs, or if the distribution center are located a far distance from the fixed processing plants, implementing a mobile plant in combination with a fixed plant can benefit decision makers.

As a result, from the economic viewpoint, if bio-oil developers are experiencing expensive truck costs, or if the distribution center are located a far distance from the fixed processing plants, implementing a mobile plant in combination with a fixed plant can be of economic benefit. However, the results show a slightly larger carbon footprint due to use of a mobile plant. This demonstrates the tradeoffs that arise when simultaneously considering various sustainability performance metrics. Given these options, a decision maker would need to place judgment on the value of reducing supply chain carbon footprint to get the most benefit from implementing a mobile plant in the woody biomass supply chain.

The work also highlights the importance of focusing technology development efforts to reduce the costs and environmental impacts of mobile processing units.

5.4 Limitations

First, the model presented in this study has been implemented in a non-dynamic case study, which led to underestimating the ability of the optimization model in investigation of time impact on the result. Time can have a major influence on the overall cost and as a result on the optimal number and location of plants, since timber harvesting varies by season. The model presented in the case study considered a one year time horizon and omitted the effect of harvesting and non-harvesting periods, as well as the inventory cost of biomass. It is expected that inventory levels at a fixed bio-oil facility will vary greatly throughout the year. To attain a reliable answer to the challenge of implementing a mobile plant aligned with a fixed plant, future studies should focus on a dynamic model where these factors can be evaluated.

The second limitation of this study is related to the choice of measure for the amount of woody waste. The woody waste amount used in the model was based on mass rather than volume. The relative density of woody waste, especially leftover slash, can widely vary and impact the number of trips required, which has a direct effect on cost and carbon footprint. However, this model only focused on the weight of the woody waste, by assuming most of the mass to be non-merchantable timber, and related the number of trips to the truck capacity in tons. As it was proved in previous section, transportation costs and activities have major impact on the level of mobile plant utilization. As a result, considering the volume of woody waste instead of mass is crucial when the feedstock in the supply chain is primarily leftover slash.

The third limitation of this study is in only considering one-way, rather than two-way transportation in the model. It was assumed that an unlimited number of trucks were available at each terminal to transport woody waste and bio-oil to their final destinations and there is no need to use the same truck to continue the transportation activity. This assumption ignores the full impact of transportation on the overall cost and carbon footprint emission of a transportation activity.

A related limitation is in the distance calculation method using GIS. Since forest and highway roads were contained in the same map layer, these distances had to be resolved by hand, and a limited number of routes could be calculated given the time constraints of the research. Thus, all route alternatives to each mobile unit could not be explored and, instead, defaulted to a fixed facility. This likely had the effect of artificially increasing the amount of waste transported to fixed facilities, when nearby mobile units may have been viable.

The last primary limitation in this research is the omission of loading and unloading cost of biomass due to lack of sufficient data. This cost can have effect on the final result since it can be categorized under the transportation activity cost. In this model, it was assumed that highway trucks are incapable of maneuvering in the forest and, as a result, two types of trucks were needed to transfer the woody waste from harvesting zones to the fixed plants. The cost of unloading woody waste from an in-forest truck and loading them onto the highway truck at the forest road-main road junction had been ignored due to lack information.

Through addressing these limitations existed in the model, a more accurate result will be attainable in the region scale problem.

5.5 Future Work

In this section, different opportunities for developing a sustainable woody biomass to bio-oil supply chain modeling are suggested to provide a vivid path for future research in this field.

First, the mathematical model presented in this study does not consider the demand side of the supply chain and concentrates on improving the supply side. As the results gained in sensitivity analysis reveal, the location of the bio-oil distribution centers and the amount of woody waste that should be processed have impact on the combination of fixed and mobile plants. Accurate determination of the demand level in the region in addition to exact location of the end user would have an impact on the overall cost of the system, carbon footprint, and the optimal number and location of mobile and fixed plants.

Second, the mathematical model presented in this study can be improved by discovering the location of fixed and mobile plants in addition to developing a combination of these two types of processing plants through mathematical programming. Currently, the model obliges the user to determine the desired location of processing plants. Adding the attribute of site selection into the optimization model will open up evaluation of other opportunities that exist in the woody waste to bio-oil supply chain.

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Appendices

Appendix 4.1- Distribution of Woody Waste Amount in Different Harvesting areas Located in "Forest Grove" District

Forest District	Harvesting area	Amount of non-merchantable product (in US ton)
Forest Grove	Van Salmon	280.43
	Cochran the Third	156.26
	Steel Shield	276.16
	Holey Oak	140.33
	Bobcat Tango	90.50
	Rocky Raccoon	188.14
	Grindstone Cowboy	410.75
	Hags To Riches	295.70
	Steelhead Falls	270.71
	Mighty Lyda	288.86
	SW Barney	253.05
	Rusty Ford	307.38
	Schmidlin	256.20
	Month O Sundays	203.88
	Reeher Wheel	24.34
	Step N' Wolf	150.79
	Rogers Riddle	23.82
	Roaring West	108.19

Appendix 4.2- Distribution of Woody Waste Amount in Different Harvesting Areas Located in "Tillamook" District

Forest District	Harvesting area	Amount of non-merchantable product (in US ton)
Tillamook	Cronin the Barbarian	1163.10
	Big Three Junction	811.94
	Sharp Ridge	75.86
	Lost Buck	309.84
	Steam Donkey	297.49
	Downtown	456.91
	McKenny Flats	347.62
	Fall Ridge	455.70
	North Morris	366.75
	Hansen Falls	26.36
	Helloff Point	522.75
	Clay Tunnel	265.44
	McPherson Ridge	577.02
	Four Aces	191.07
	North Coal	9.69
	Waterhouse	248.57
	Tillson Ridge	217.59
	Sargent Jordan	51.14

Appendix 4.3- Distribution of Woody Waste amount in Different Harvesting Areas Located in "Astoria" district

Forest District	Harvesting area	Amount of non-merchantable product (in US ton)
Astoria	Greasy Alder	84.32
	Courtside	141.39
	Buck Ranch	233.35
	Winslow	483.74
	Summit Combo	134.24
	Happy Gillmore	30.42
	Modified Green	330.54
	Mombo Combo	227.26
	Buzzard Ridge Combin	272.29
	Ridge 77	111.28
	Alderberry	144.76
	Puma Punch	153.17

Appendix 4.4- Candidate Mobile plants and Respective Harvesting areas (Including Distance and Woody Waste Amount)

Potential Mobile plants	Harvesting area	In-forest distance (in mile)	Amount of non-merchantable product (in US ton)
Mobile Plant (1)	Water House	9.61	248.57
	Fall Ridge	4.09	455.70
	Hansen Fall	1.69	26.36
	Four Ace	4.16	191.08
	North Coal	8.36	9.69
	Helloff Point	2.9	522.75
Mobile Plant (2)	McKenny flats	14.73	347.62
	Lost Buck	5.79	309.84
	McPhers on Ridge	15.61	577.02
Mobile Plant (3)	Cronin Barbarian	23.86	1163.10
	Big Tree Junction	10.12	811.94
Mobile Plant (4)	North Morris	8.94	366.75
	Clay Tunnel	7.9	265.44
Mobile Plant (5)	Steel Sheild	4.84	276.16
	Steelhead Fall	10.67	270.71
	Rock Raccon	3.65	188.14
	Van Salmon	6.59	280.43
	Rusty Ford	6.61	307.38

Appendix 4.4 (Continued)

Potential Mobile plants	Harvesting area	In-forest distance (in mile	Amount of non-merchantable product (in US ton)
Mobile Plant (6)	Cochran the third	5.06	156.26
	Bobcat Tango	15.96	90.50
	Reheer wheel	5.93	24.34
	Step N wolf	4.35	150.79
Mobile Plant (7)	Rogers riddle	13.58	23.82
	Schmidilin	14.09	256.20
	Hages to Rich	6.96	295.70
Mobile Plant (8)	DownTown	18.04	456.91
	Nobel View	18.17	230.04
	Sargent Jordan	24.35	51.14
	Mighty Lyda	17.95	288.86
	steam donkey	19.23	297.49
	Month o Sunday	13.90	203.88
	Roaring West	14.19	108.19
	SW Barney	20.30	253.05
	Grindson Cowboy	14.86	410.75
Mobile Plant (9)	Sharp Ridge	16.99	75.86
	Tilsson Ridge	19.41	217.59

Appendix 4.4 (Continued)

Potential Mobile plants	Harvesting area	In-forest distance (in mile)	Amount of non-merchantable product (in US ton)
Mobile Plant (10)	Puma Punch	2.43	153.17
	Buzzard Ridge Combine	8.27	272.29
Mobile Plant (11)	Alderberry	8.02	144.76
	Courside	8.08	141.39
Mobile Plant (12)	Summit Combo	5.98	134.24
	Happy Gillmore	4.5	30.42
Mobile Plant (13)	Buck Ranch	5.87	233.35
	Winslow	5.55	483.74
	Ridge 77	9.58	111.28
Mobile Plant (14)	Grease Alder	4.12	84.32
	Mombo Combo	5.7	227.26
Mobile Plant (15)	Modified Green	0	330.54
Mobile Plant (16)	Holey Oak	0	140.33

Appendix 4.5- Distance Between Harvesting Areas and The Fixed Plant Located at the Center of Tillamook County

Harvesting area	In-forest distance (in mile)	Highway distance (in mile)	Total distance (in mile)
Van Salmon	0.369	16.4	16.769
Cochran the Third	3.94	1.255	5.195
Steel Shield	11.83	6.94	18.77
Holey Oak	3.73	10.37	14.1
Bobcat Tango	2.53	13.71	16.24
Rocky Raccoon	10.88	13.66	24.54
Grindstone Cowboy	11.79	7.05	18.84
Hags To Riches	3	18.93	21.93
Steelhead Falls	20.87	7.34	28.21
Mighty Lyda	12.73	7.29	20.02
SW Barney	25.7202	7.3388	33.059
Rusty Ford	0.63	31.7	32.33
Schmidlin	5.83	30.73	36.56
Month O Sundays	2.49	30.78	33.27
Reeher Wheel	2.42	30.2	32.62
Step N' Wolf	1.94	30.84	32.78
Rogers Riddle	5.52	30.74	36.26
Roaring West	35.47	7.3	42.77
Cronin the Barbarian	24.84	7.3	32.14
Big Three Junction	19.68	18.26	37.94
Sharp Ridge	19.94	24.78	44.72
Lost Buck	24.89	18.26	43.15
Steam Donkey	22.11	18.29	40.4

Downtown	17.39	23.51	40.9
McKenny Flats	4.24	26.06	30.3
Fall Ridge	1.77	81.4	83.17
North Morris	59.39	7.28	66.67
Hansen Falls	56.3	7.03	63.33
Helloff Point	45.33	7.34	52.67
Clay Tunnel	32.24	18.26	50.5
McPherson Ridge	9.01	35.22	44.23
Four Aces	10.64	35.17	45.81
North Coal	40.28	7.29	47.57
Waterhouse	56.96	7.3	64.26
Tillson Ridge	56.69	7.3	63.99
Sargent Jordan	61.19	7.3	68.49
Noble View	63.61	7.3	70.91
Greasy Alder	66.19	7.3	73.49
Courtside	29.48	18.27	47.75
Buck Ranch	2.85	82.1	84.95
Winslow	11.67	30.71	42.38
Summit Combo	4.33	29.11	33.44
Happy Gillmore	1.8	36.1	37.9
Modified Green	12.32	32.34	44.66
Mombo Combo	24.63	6.97	31.6
Buzzard Ridge Combin	23.98	7.01	30.99
Ridge 77	29.71	6.46	36.17
Alderberry	23.61	7.01	30.62
Puma Punch	15.74	23.47	39.21

Appendix 4.6- Distance between Harvesting Areas and The Fixed Plant Located at the Center of Clatsop County

Harvesting area	In-forest distance (in mile)	Highway distance (in mile)	Total distance (in mile)
Van Salmon	5.27	71.54	76.81
Cochran the Third	39.36	49.28	88.64
Steel Shield	40.57	49.23	89.8
Holey Oak	27.81	49.25	77.06
Bobcat Tango	26.7	49.25	75.95
Rocky Raccoon	30.85	43.41	74.26
Grindstone Cowboy	34.52	49.26	83.78
Hags To Riches	19.45	49.23	68.68
Steelhead Falls	8.01	56.41	64.42
Mighty Lyda	9.71	49.35	59.06
SW Barney	3.67	56.4	60.07
Rusty Ford	0.64	61.72	62.36
Schmidlin	8.64	54.53	63.17
Month O Sundays	5.55	54.41	59.96
Reeher Wheel	4.75	54.51	59.26
Step N' Wolf	1.94	57.94	59.88
Rogers Riddle	8.29	54.33	62.62
Roaring West	5.16	47.22	52.38
Cronin the Barbarian	9.65	49.25	58.9
Big Three Junction	10.92	42.85	53.77
Sharp Ridge	11.06	42.85	53.91
Lost Buck	3.17	42.7	45.87
Steam Donkey	7.98	42.85	50.83

Downtown	8.62	43.35	51.97
McKenny Flats	28.42	43.42	71.84
Fall Ridge	1.83	2.13	3.96
North Morris	1.19	19.23	20.42
Hansen Falls	0.63	22.12	22.75
Helloff Point	1.7	35.37	37.07
Clay Tunnel	3.71	37.2	40.91
McPherson Ridge	4.91	50.96	55.87
Four Aces	6.21	50.98	57.19
North Coal	4.47	6	10.47
Waterhouse	10.47	27.54	38.01
Tillson Ridge	10.1	27.6	37.7
Sargent Jordan	1.67	33.4	35.07
Noble View	15.14	22.21	37.35
Greasy Alder	17.87	22.13	40
Courtside	2.04	43.65	45.69
Buck Ranch	2.36	89.09	91.45
Winslow	7.88	43.32	51.2
Summit Combo	25.42	43.41	68.83
Happy Gillmore	1.82	61.61	63.43
Modified Green	12.52	62.26	74.78
Mombo Combo	38.07	43.43	81.5
Buzzard Ridge Combin	45.13	43.31	88.44
Ridge 77	50.95	43.29	94.24
Alderberry	34.07	43.43	77.5
Puma Punch	10.61	43.44	54.05

Appendix 4.7- Distance between Harvesting Areas and The Fixed Plant Located at the Center of Washington County

Harvesting area	In-forest distance (in mile)	Highway distance (in mile)	Total distance (in mile)
Van Salmon	32.93	29.91	62.84
Cochran the Third	5.1	46.85	51.95
Steel Shield	35.6	12.38	47.98
Holey Oak	3.72	34.61	38.33
Bobcat Tango	11.51	24.65	36.16
Rocky Raccoon	7.73	20.92	28.65
Grindstone Cowboy	16.15	24.62	40.77
Hags To Riches	3.33	28.84	32.17
Steelhead Falls	15.31	29.88	45.19
Mighty Lyda	17.74	28.81	46.55
SW Barney	21.08	28.87	49.95
Rusty Ford	0.64	63.61	64.25
Schmidlin	8.66	56.32	64.98
Month O Sundays	5.48	56.37	61.85
Reeher Wheel	4.82	56.36	61.18
Step N' Wolf	1.95	59.12	61.07
Rogers Riddle	8.24	56.35	64.59
Roaring West	21.05	28.68	49.73
Cronin the Barbarian	16.5	28.84	45.34
Big Three Junction	15.37	18.69	34.06
Sharp Ridge	1.29	25.75	27.04
Lost Buck	10.49	18	28.49
Steam Donkey	11.72	18.69	30.41

Downtown	10.43	15.25	25.68
McKenny Flats	4.2	22.11	26.31
Fall Ridge	1.63	67.33	68.96
North Morris	1.21	49.18	50.39
Hansen Falls	0.71	46.3	47.01
Helloff Point	1.69	33.11	34.8
Clay Tunnel	1.55	28.69	30.24
McPherson Ridge	5.03	52.8	57.83
Four Aces	6.33	52.74	59.07
North Coal	14.8	28.64	43.44
Waterhouse	15.97	29.56	45.53
Tillson Ridge	15.7	29.6	45.3
Sargent Jordan	1.65	50.54	52.19
Noble View	11.35	43.2	54.55
Greasy Alder	13.93	43.29	57.22
Courtside	2.08	24.71	26.79
Buck Ranch	2.84	41.11	43.95
Winslow	3.48	20.08	23.56
Summit Combo	4.33	19.01	23.34
Happy Gillmore	1.91	11.95	13.86
Modified Green	4.76	14.77	19.53
Mombo Combo	18.81	12.4	31.21
Buzzard Ridge Combin	3.5	26.86	30.36
Ridge 77	7.93	26.86	34.79
Alderberry	14.88	12.35	27.23
Puma Punch	11.01	15.24	26.25

Appendix 4.8- Distance between Harvesting Areas and The Fixed Plant Located at the Center of Columbia County

Harvesting area	In-forest distance (in mile)	Highway distance (in mile)	Total distance (in mile)
Van Salmon	32.97	60.39	93.36
Cochran the Third	5.18	77.36	82.54
Steel Shield	11.74	70.95	82.69
Holey Oak	3.8	65.07	68.87
Bobcat Tango	11.55	55.14	66.69
Rocky Raccoon	7.46	51.42	58.88
Grindstone Cowboy	16.11	55.14	71.25
Hags To Riches	3.32	59.38	62.7
Steelhead Falls	34.22	35.75	69.97
Mighty Lyda	31.52	35.78	67.3
SW Barney	38.43	35.75	74.18
Rusty Ford	0.62	80.73	81.35
Schmidlin	8.59	73.5	82.09
Month O Sundays	5.51	73.46	78.97
Reeher Wheel	4.78	73.48	78.26
Step N' Wolf	1.92	76.9	78.82
Rogers Riddle	8.22	73.47	81.69
Roaring West	21.09	45.77	66.86
Cronin the Barbarian	30.34	35.73	66.07
Big Three Junction	1.21	42.83	44.04
Sharp Ridge	15.37	35.78	51.15
Lost Buck	9.77	35.74	45.51
Steam Donkey	11.77	35.76	47.53

Downtown	7.42	38.02	45.44
McKenny Flats	4.17	52.7	56.87
Fall Ridge	1.67	84.34	86.01
North Morris	1.1	66.37	67.47
Hansen Falls	0.64	63.52	64.16
Helloff Point	1.09	50.83	51.92
Clay Tunnel	1.54	45.78	47.32
McPherson Ridge	5.02	69.88	74.9
Four Aces	6.03	70.14	76.17
North Coal	14.79	45.79	60.58
Waterhouse	16.01	46.66	62.67
Tillson Ridge	15.7	46.71	62.41
Sargent Jordan	1.68	67.59	69.27
Noble View	11.35	60.37	71.72
Greasy Alder	13.98	60.36	74.34
Courtside	1.99	41.86	43.85
Buck Ranch	2.4	3.44	5.84
Winslow	5.6	35.73	41.33
Summit Combo	4.29	49.59	53.88
Happy Gillmore	1.82	42.62	44.44
Modified Green	4.8	52.34	57.14
Mombo Combo	16.2	50.35	66.55
Buzzard Ridge Combin	3.51	64.45	67.96
Ridge 77	8.9	64.47	73.37
Alderberry	12.32	50.25	62.57
Puma Punch	8.41	38.1	46.51

Appendix 4.9- Distance between Mobile Plant Candidates and The Fixed Plant Located at the Center of Tillamook County

Potential Mobile Plant	Total distance (in mile)
Mobile Plant (1)	34.27
Mobile Plant (2)	28.52
Mobile Plant (3)	43.3
Mobile Plant (4)	28.55
Mobile Plant (5)	44.83
Mobile Plant (6)	36.65
Mobile Plant (7)	39.87
Mobile Plant (8)	28.02
Mobile Plant (9)	13.14
Mobile Plant (10)	43.36
Mobile Plant (11)	55.48
Mobile Plant (12)	66.62
Mobile Plant (13)	67.45
Mobile Plant (14)	75.42
Mobile Plant (15)	83.17
Mobile Plant (16)	84.95

Appendix 4.10- Distance between Mobile Plant Candidates and The Fixed Plant Located at the Center of Clatsop County

Potential Mobile Plant	Total distance (in mile)
Mobile Plant (1)	60.75
Mobile Plant (2)	60.81
Mobile Plant (3)	50.96
Mobile Plant (4)	60.86
Mobile Plant (5)	48.17
Mobile Plant (6)	57.78
Mobile Plant (7)	69.99
Mobile Plant (8)	86.02
Mobile Plant (9)	82.32
Mobile Plant (10)	57.36
Mobile Plant (11)	35.62
Mobile Plant (12)	24.12
Mobile Plant (13)	36.39
Mobile Plant (14)	41.75
Mobile Plant (15)	3.96
Mobile Plant (16)	91.45

Appendix 4.11- Distance between Mobile Plant Candidates and The Fixed Plant Located at the Center Washington County

Potential Mobile Plant	Total distance (in mile)
Mobile Plant (1)	62.59
Mobile Plant (2)	45.3
Mobile Plant (3)	48.35
Mobile Plant (4)	38.45
Mobile Plant (5)	26.39
Mobile Plant (6)	23.23
Mobile Plant (7)	23.47
Mobile Plant (8)	38.57
Mobile Plant (9)	51.12
Mobile Plant (10)	59.46
Mobile Plant (11)	33.94
Mobile Plant (12)	50.32
Mobile Plant (13)	48.81
Mobile Plant (14)	58.41
Mobile Plant (15)	68.96
Mobile Plant (16)	43.95

Appendix 4.12- Distance between Mobile Plant Candidates and The Fixed Plant Located at the Center of Columbia County

Potential Mobile Plant	Total distance (in mile)
Mobile Plant(1)	79.7
Mobile Plant(2)	69.72
Mobile Plant(3)	65.41
Mobile Plant(4)	59.12
Mobile Plant(5)	43.53
Mobile Plant(6)	46.31
Mobile Plant(7)	53.94
Mobile Plant(8)	70.89
Mobile Plant(9)	81.62
Mobile Plant(10)	76.53
Mobile Plant(11)	52.29
Mobile Plant(12)	67.2
Mobile Plant(13)	65.91
Mobile Plant(14)	75.44
Mobile Plant(15)	86.01
Mobile Plant(16)	5.84

Appendix 4.13 –Illustration of Optimal Processing Plants Location on the Map