Reducing the cost and environmental impact of integrated fixed and mobile bio-oil refinery supply chains

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ARTICLE INFO

ABSTRACT

The call to decrease reliance on fossil fuels to reduce impacts on the environment and improve energy independence has created new duties and responsibilities within society. As one approach, mobile bio-oil refineries have been developed to facilitate the production of bio-oil near the source of underutilized forest harvest residues. These mobile refineries are expected to improve the robustness of woody biomass to bio-oil supply chains by reducing overall supply chain costs and environmental impacts. The use of mobile refineries in combination with large-scale non-mobile refineries, however, must be examined to better understand the potential economic and environmental benefits and drawbacks of such a supply chain. The research presented herein develops a mathematical model capable of helping decision makers in determining the optimal combination and location of fixed refineries and mobile refineries for a known quantity of woody biomass and a given set of harvesting locations by considering capital, operational, and transportation costs. A hypothetical case for northwest Oregon, USA is applied to verify the mathematical model. The supply chain environmental impacts are assessed by considering the carbon footprint of the transportation activities and the bio-refinery infrastructure. The results indicate that the use of a mobile refinery along with a fixed refinery is more suitable when transportation costs and distances increase. It is also found that the capital intensity of mobile refineries can influence the importance of their role. High capital cost can be detrimental to their application within a mixed-mode bio-oil supply chain.

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1. Introduction

Due to the increasing cost of fossil fuels, their impacts on the environment, and an increasing call for energy independence, many countries are focusing on technology and policy mechanisms for substituting fossil sources with renewables, e.g., biomass, wind, and hydro, to achieve improved energy sustainability performance. According to the U.S. Energy Information Administration, the fossil fuel share of total energy use will decrease from 82% in 2011 to 78% in 2040, while the renewables share, including bio-fuels, is expected to increase from 9% to 13% in the same time period (USEIA, 2014). Bio-oil can be produced from forest harvest residues (FHR). Bio-oil from woody biomass (WB) is a potential energy source in

terms of reduced social, environmental, and economic impacts since it is a by-product of harvesting, represents a fire hazard, impedes planting of seedlings, harbors rodents that eat seedlings, and its combustion is considered carbon neutral (Page-Dumroese et al., 2009; Steele et al., 2012), particularly when compared to conventional disposal methods using fire. The main applications of bio-oil include combustion in engines, turbines, and boilers, as well as production of chemicals, transportation fuels, and hydrogen (Czernik and Bridgwater, 2004; Bridgwater, 2012; Kersten and Garcia-Perez, 2013). Optimization of biomass to bio-oil supply chains (SCs), however, is required to assist industry in supplying the market with a product cognizant of the three domains of sustainability, i.e., economic, environmental, and social (Mullaney et al., 2002).

The research herein is motivated by the premise that bio-oil can be considered an economically and technically feasible alternative for fossil fuel-based applications. Current bio-oil output is not sufficient to meet societal demand, however, due to high costs of

FHR transportation and the scarcity of bio-oil refineries (Searcy et al., 2007). A recent comprehensive study concluded that the conversion process itself, in addition to the SC barriers, is inhibiting commercialization of bio-refineries (Sharma et al., 2013). The application of small scale and transportable bio-oil refineries has been investigated in recent years to more economically produce greater quantities of bio-oil. Mobile refineries (MRs) have been fabricated to be placed in the forest to produce bio-oil from FHR (Badger and Fransham, 2006). It is posited that if MRs can be utilized in a SC along with fixed (non-mobile) refineries (FRs), the limitations of producing a sufficient volume of bio-oil can be overcome, and this source of renewable energy can be deployed more effectively and efficiently.

To improve the robustness of bio-oil SC networks and to be able to respond to rapid growth in fuel consumption, different SC schemes consisting of combinations of current technologies and techniques are required. As such, mixed-mode bio-oil SCs, including the utilization of both FRs and MRs, can be part of the solution to meet increasing consumer fuel demands, while mitigating the impacts associated with fossil fuels. Previous research has proposed approaches to improving biomass to bio-fuel SCs, either by applying new techniques and methodologies for different entities or by focusing on the whole SC from a system perspective. The effect of integrating MRs along with FRs within a single SC to produce bio-oil from WB has remained unanswered. The next section reviews prior research to highlight the limitations of current approaches.

1.1. Literature review

To understand the nature of bio-energy, it is important to introduce the different types of biomass that may be used in conversion centers (Frombo et al., 2009). Agricultural, municipal, and forest harvest and agricultural products can be used to produce bio-fuels, e.g., bio-ethanol, bio-methanol, bio-diesel and bio-oil. However, since the supply and cost of agricultural products, such as corn, are uncertain, recent studies have focused on utilizing biomass residues, such as FHR, to produce bio-energy (Aden et al., 2002). The USDA Forest Service suggested that approximately 73 million acres of national forest land in the United States have an excessive amount of forest biomass, which can be considered a reliable source for producing bio-oil (Troyer et al., 2003).

Bio-oil can be produced from degradable biomass using the fast pyrolysis process. FHR is the most common biomass source used in fast pyrolysis (Mullaney et al., 2002). The use of low quality wood chips created from residues remaining after thinning and harvesting processes at roadside in the forest has a positive effect of creating job opportunities and improving the overall economy (Mullaney et al., 2002). The high costs of collection and transportation of FHR are considered a barrier to its use as compared to other forms of biomass. Since bio-oil (18–21 MJ/kg) has higher energy density than green whole tree chips (8.53 MJ/kg), transport of bio-oil is energetically more advantageous compared to raw biomass transport (Badger and Fransham, 2006). According to Badger (2002), the high moisture content levels and low energy density of WB, compared to fuel in liquid form, are the key drivers for high transportation cost. An analytical SC model developed by Allen et al. (1998) found that 20–50% of the overall cost of SC can be attributed to transportation activities.

Several studies have investigated the trade-offs between process operation and transportation costs. Polagye et al. (2007) and Granatstein et al. (2009) argued that the biofuel production using mobile and/or transportable facilities is more costly than fixed and/or relocatable facilities. Conversely, You and Wang (2011) and Yue et al. (2014) reported that a combination of pretreatment

facilities and upgrading facilities within a region of 60–135 km² has lower cost than a fixed facility alone. Therefore, further study is needed to determine the competitiveness of mobile and transportable facility. A wheel-mounted and transportable refinery capable of processing WB at rate of 13.6 metric dry tons (15 US dry tons) per day has been fabricated and reported in the literature (Badger et al., 2010; Mirkouei and Haapala, 2015). The unit can be placed next to in-forest collection areas and produce bio-oil through the fast pyrolysis process. Due to the novel nature of MRs, previous studies focusing on improving the biomass SC network through mathematical models have failed to address a key question: *How many MRs and FRs should work simultaneously in an integrated SC to process a specific amount of WB in an optimal manner?*

As Fig. 1 illustrates, the bio-fuel SC consists of feedstock production (WB), collection and transportation, processing and storage, and delivery to the end user or to storage. An optimal SC is dependent on critical decision making with regard to each of these SC entities, as well as at the system level, to ensure all goals and needs are met. The major goal is to meet the bio-oil demand of the region by processing FHR left at roadside after log making in selected forests. A critical need is to determine optimal SC costs, which can be used to define the lowest cost transportation and capital infrastructure alternatives for the system.

The issues of harvesting and collection, storage location and layout, and delivery have been investigated in previous studies. Collection and harvesting methods have been analyzed to create an in-depth solution to avoid biomass logistics pitfalls. The cost analysis of harvesting switch grass in round bales and an economic study comparing round and square bales of switch grass have been performed by Cundiff and Marsh (1996), respectively. The impact of covered on-field storage on the delivery cost, intermediate storage scenarios, and adjacent storage layout on the overall SC cost have been analyzed (Cundiff et al., 1997; Papadopoulos and Katsigiannis, 2002; Tatsiopoulos and Tolis, 2003). In most cases, low-cost storage layouts have been identified. Rentizelas et al. (2009) addressed a key research gap in the storage and collection stage by proposing three types of storage layouts for agricultural biomass, i.e., an adjacent warehouse with drying capability, metal roof storage, and ambient storage without drying infrastructure. Handling and storage of WB is different than agricultural biomass, since WB needs to be chipped after collection to be ready for the conversion process. Thus, the decision of implementing centralized or decentralized chipper equipment has been studied by Gronalt and Rauch (2007) through a heuristic approach.

In addition to research focusing on the impact of individual stages on the whole SC, other studies have developed various methods and approaches to improve the biomass SC from a systems perspective. Sandia National Laboratories provided a dynamic model that considers various types of biomass to meet the national demand for cellulosic ethanol (West et al., 2009). Zhang et al. (2013) proposed a mixed integer linear programming (MILP) model to minimize the overall cost of producing ethanol from switch grass while considering all stages in the SC network. Another MILP model was developed by Zhu et al. (2011) to assess restrictions on harvesting seasons and scattered geographical distribution on the overall system performance. Eriksson and Björheden (1989) presented a linear programming (LP) model to minimize the transportation cost of pellet fuel from numerous supply sites to a central heating plant. However, this model failed to guide decision makers about whether to use more harvesting area or sawmills to meet demand. This drawback was addressed by Gunnarsson et al. (2004) by proposing a large and comprehensive MILP model for a forest fuel network.
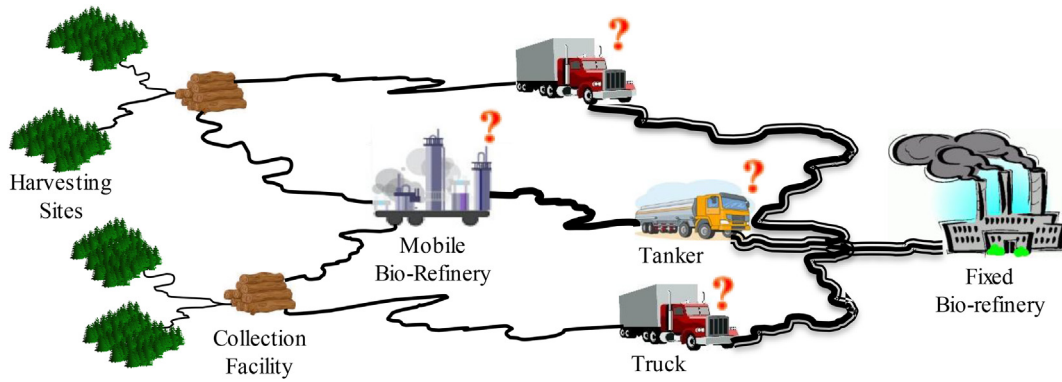
Fig. 1. Schematic biomass to bio-oil supply chain network.

1.2. Motivation

Previous mathematical models are limited in their ability to answer the question posed above in two key aspects: 1) WB has not been considered as a feedstock to produce bio-oil and 2) the role of a MR has not been addressed when accompanied with an FR in the SC. The goal of the mathematical model presented in this study, therefore, is to determine the number of FRs and MRs that are needed to process a known amount of FHR while minimizing overall SC cost. The cost optimization model developed below focuses on transportation costs and the capital and operational costs of mobile and fixed bio-oil refineries. Subsequently, the environmental impact, in terms of carbon footprint (mass of CO_2 equivalent emissions), is assessed for various alternatives.

Truck travel time is an important factor to consider in answering where the MRs should be located and which harvesting area will be served by each refinery in fixed and mobile bio-oil refinery decision making. Geographical information system (GIS)-based approaches have been widely used in prior research to address transportation and location-allocation problems. Muttiah et al. (1996) implemented GIS in a decision support system to identify waste disposal sites, for example. A public facility location was also identified by Yeh and Chow (1996) by integrating a GIS approach with a location-allocation model. In the model presented below, truck travel distance is considered.

In the research reported herein, a combination of FRs and MRs that minimizes cost is identified by developing and applying an MILP mathematical model. GIS software is used to calculate the shortest path between harvesting areas and refineries. Next, carbon footprint (CF) analysis is undertaken to estimate the environmental impact of the resulting SC. Finally, the effect of this decision making approach on the design of a hypothetical bio-oil SC in northwest Oregon, USA is explored, and the effect of key factors on the selected economic and environmental measures is analyzed through sensitivity analysis.

2. Methodology

The MILP model presented in this research is developed to minimize WB to bio-oil SC cost. Operation of each fixed and mobile refinery in a predetermined population to define the SC network is facilitated using a binary variable in the mathematical model. The major cost elements of the model include transportation cost, refinery operational and capital costs, and storage cost. Since the focus of the model is on the optimal number of fixed and mobile refineries needed to process a known amount of WB, the model considers the supply side, rather than the demand

side of the SC, i.e., it is assumed that all bio-oil will be utilized in existing markets. Sections 2.1 and 2.2 explain the formulation of the objective function and constraints in greater detail, while Section 2.3 describes the approach for evaluating environmental impacts.

2.1. Model objective function

The objective of the proposed MILP model is to minimize the overall cost of a mixed-mode biomass SC by considering two major cost elements. First, the transportation activities involved in the network consist of delivering WB from the forest to the mobile or FR using both in-forest and main roads, as well as delivering bio-oil from the MR to the bio-oil storage at an FR location. Second, costs account for establishing and operating the FRs and MRs, and for the bio-oil and biomass storage facilities adjacent to the FRs. The objective function (Z) to be minimized is represented in Eq. (1).

$$\text{Min } Z = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7 + C_8 + C_9 \tag{1}$$

Each of the terms (C_1–C_9) in Eq. (1) is defined in sequence below. The model nomenclature is reported in Annex A. The cost (C_1) of WB transportation from each harvesting area to the selected MR for time period (t) is calculated (Eq. (2)) as the summation of the product of D_{ijt}, the shortest distance between the harvesting area (i) and the MR location (j), C_s, operational cost of an in-forest tractor trailer (small tractor trailer), and n_{ijt}, the required number of in-forest tractor trailer trips for each route.

$$C_1 = \sum_i \sum_j \sum_t D_{ijt} \cdot C_s \cdot n_{ijt} \tag{2}$$

The cost (C_2) of in-forest transportation of WB from each harvesting areas to the main road junction (k) is calculated (Eq. (3)) as the summation of the product of D_{ikt}, the shortest distance from the harvesting area to the main road, C_s, operational cost of an in-forest tractor trailer (single trailer), and n_{ikt}, required number of in-forest tractor trailer trips for each route.

$$C_2 = \sum_i \sum_k \sum_t D_{ikt} \cdot C_s \cdot n_{ikt} \tag{3}$$

The cost (C_3) of on-road (highway) transportation of WB from each main road junction to the FR (l), is calculated (Eq. (4)) as the summation of the product of D_{klt}, the shortest distance from the highway to the FR, C_{2s}, operational cost of an on-highway tractor trailer (truck tractor with two trailers), and n_{klt}, the required number of on-highway tractor trailer trips to haul the biomass transferred from the in-forest tractor trailers for each route. Travel

cost on a specific road class is considered directly proportional to distance.

$$C_3 = \sum_k \sum_l \sum_t D_{klt} \cdot C_{2s} \cdot n_{klt} \tag{4}$$

In-forest trucks have a smaller capacity but greater maneuverability, as reflected in Equations (2)–(4) (Schroeder et al., 2007). The cost (C_4) of transporting bio-oil from a mobile to an FR is calculated (Eq. (5)) as the summation of the product of D_{jlt}, the shortest distance from the MR to the FR, C_{tnk}, operational cost of a bio-oil tanker, and n_{jlt}, the required number of bio-oil tankers trips to transport produced bio-oil for each route.

$$C_4 = \sum_j \sum_l \sum_t D_{jlt} \cdot C_{tnk} \cdot n_{jlt} \tag{5}$$

Equations (6)–(9) calculate the annual cost of the FRs (C_5), the MRs (C_6), and associated bio-oil (C_7) and biomass (C_8) storage facilities. In this model, it is assumed that the bio-oil produced by an MR will be held in storage adjacent to the FR. These formulations are defined as the products of C_{fix}, C_{mob}, C_{st_oil}, and C_{st_mass}, which are the annualized capital and operational costs of the FR, MR, bio-oil storage facility, and biomass storage facility, respectively, and the related binary variables (i.e., α, β, γ, and δ) indicating whether entity is in operation. Operational costs for each refinery consist of electricity, grinding or chipping, chemical supplies, and natural gas, which are dependent on the size of the refinery.

$$C_5 = \sum_l \sum_t \alpha_{lt} \cdot C_{fix} \tag{6}$$

$$C_6 = \sum_j \sum_t \beta_{jt} \cdot C_{mob} \tag{7}$$

$$C_7 = \sum_l \sum_t \gamma_{lct} \cdot C_{st_oil} \tag{8}$$

$$C_8 = \sum_l \sum_t \delta_{lct} \cdot C_{st_mass} \tag{9}$$

The holding cost (C_9) of WB is calculated (Eq. (10)) as the summation of the product of C_{in}, the inventory cost of storing WB, and X_{klt}, the amount of WB that will be stored in each biomass storage facility.

$$C_9 = \sum_k \sum_l \sum_t C_{in} \cdot X_{klt} \tag{10}$$

Since the fast pyrolysis processing technology is assumed to be the same for each type of refinery, the processing costs (e.g., collection and grinding costs) are not considered in the formulation of the objective function. Recent research has modeled economies of scale of bio-oil production, but uncertainties remain regarding scalability of pyrolysis reactors (Arbogast et al., 2012).

2.2. Model constraints

The constraints applied in optimizing the objective function presented in the previous section are defined below. Equations (11)–(14) ensure that the number of in-forest tractor-trailer trips (for transport to MRs or to main road junctions), on-highway tractor-trailer trips, and bio-oil tanker truck trips, respectively, have sufficient capacity to transport the WB and bio-oil.

$$n_{ijt} \geq X_{ijt}/CAP_s \quad \forall_i \in I, \quad \forall_j \in J, \quad \forall_t \in T \tag{11}$$

$$n_{ikt} \geq X_{ikt}/CAP_m \quad \forall_i \in I, \quad \forall_k \in K, \quad \forall_t \in T \tag{12}$$

$$n_{klt} \geq X_{klt}/CAP_b \quad \forall_k \in K, \quad \forall_l \in L, \quad \forall_t \in T \tag{13}$$

$$n_{jlt} \geq Y_{jlt}/CAP_{tnk} \quad \forall_j \in J, \quad \forall_l \in L, \quad \forall_t \in T \tag{14}$$

Equations (15) and (16) ensure that only a specific amount of WB (determined by percentage yield, S) can be transformed to bio-oil. Percentage yield is highly dependent on the moisture content; as moisture content of WB increases, the percentage yield will decrease. Equation (17) ensures the conservation-of-flow constraints for any flow in and out of node k (forest and main road junction).

$$S * \sum_{i \in I} \sum_{t \in T} X_{ijt} - \sum_{l \in L} \sum_{t \in T} Y_{jlt} = 0 \quad \forall_i \in I, \quad \forall_l \in L, \quad \forall_t \in T \tag{15}$$

$$S * \sum_{k \in K} \sum_{t \in T} X_{klt} - \sum_{t \in T} Y_{lct} = 0 \quad \forall_k \in K, \quad \forall_t \in T \tag{16}$$

$$\sum_{i \in I} \sum_{k \in K} \sum_{t \in T} X_{ikt} - \sum_{k \in K} \sum_{l \in L} \sum_{t \in T} X_{klt} = 0 \quad \forall_i \in I, \quad \forall_l \in L, \quad \forall_t \in T \tag{17}$$

Equations (18) and (19) ensure that the flow of WB from harvesting areas is possible to the fixed and/or mobile refineries, respectively, when the selected refinery is operating.

$$\sum_{t \in T} Y_{lct} \leq M \cdot \alpha_{lt} \quad \forall_t \in T \tag{18}$$

$$\sum_{i \in I} \sum_{t \in T} X_{ijt} \leq M \cdot \beta_{jt} \quad \forall_i \in I, \quad \forall_t \in T \tag{19}$$

Equations (20) and (21) ensure that the bio-oil produced in a MR and biomass transported from harvesting areas respectively will be transported to storage adjacent to an FR if the refinery is operating. This constraint also allows bio-oil and biomass to be distributed among different FRs to optimize the flow of these products in the SC.

$$\sum_{j \in J} \sum_{t \in T} Y_{jlt} + \sum_{t \in T} Y_{lct} \leq M \cdot \gamma_{lct} \quad \forall_j \in J, \quad \forall_t \in T \tag{20}$$

$$\sum_{k \in K} \sum_{t \in T} X_{klt} \leq M \cdot \delta_{lct} \quad \forall_k \in K, \quad \forall_t \in T \tag{21}$$

Equations (22) and (23) ensure that the amount of bio-oil produced from each MR and/or FR does not exceed the capacity of the selected refinery.

$$\sum_{l \in L} \sum_{t \in T} Y_{jlt} \leq CAP_{mob} \quad \forall_l \in L, \quad \forall_t \in T \tag{22}$$

$$\sum_{t \in T} Y_{lct} \leq CAP_{fix} \quad \forall_t \in T \tag{23}$$

Equation (24) ensures that the amount of WB held at the fixed facility does not exceed the storage capacity, while Eq. (25) determines the amount of bio-oil stored in the bio-oil storage facility during a specific period of time (t). Equation (26) ensures that the

available amount of WB (θ) in each harvesting area is transported to either an MR or an FR.

$$\sum_{k \in K} \sum_{t \in T} X_{klt} \leq CAP_{st_mass} \quad \forall k \in K, \quad \forall t \in T \tag{24}$$

$$\sum_{j \in J} \sum_{t \in T} Y_{jlt} + \sum_{t \in T} Y_{lct} \leq CAP_{st_oil} \quad \forall j \in J, \quad \forall t \in T \tag{25}$$

$$\sum_{i \in I} \sum_{j \in J} \sum_{t \in T} X_{ijt} + \sum_{i \in I} \sum_{k \in K} \sum_{t \in T} X_{ikt}$$
$$\geq \theta \quad \forall i \in I, \quad \forall j \in J, \quad \forall k \in K, \quad \forall t \in T \tag{26}$$

Equations (27)–(30) are the binary constraints, Equation (31) the integer constraint, and Equation (32) the non-negativity constraint, respectively, and are applied to ensure the solution is feasible.

$$\alpha_{lt} \begin{cases} 1 & \text{if fixed refinery is working,} \\ 0 & \text{otherwise} \end{cases} \tag{27}$$

$$\beta_{jt} \begin{cases} 1 & \text{if mobile refinery is working,} \\ 0 & \text{otherwise} \end{cases} \tag{28}$$

$$\gamma_{lct} \begin{cases} 1 & \text{if bio-oil storage is working,} \\ 0 & \text{otherwise} \end{cases} \tag{29}$$

$$\delta_{lct} \begin{cases} 1 & \text{if biomass storage is working,} \\ 0 & \text{otherwise} \end{cases} \tag{30}$$

$$n_{ijt}, n_{ikt}, n_{klt}, \text{ and } n_{jlt} \text{ are integers} \tag{31}$$

$$X_{ijt}, X_{ikt}, X_{klt}, \text{ and } Y_{jlt} \geq 0 \tag{32}$$

In this section, the formulations of the objective function and constraints required for calculating the optimal number of FRs and MRs have been described. Next, Section 3 focuses on applying the mathematical model to a hypothetical case for specific region of northwest Oregon using realistic data.

2.3. Environmental impacts evaluation

Currently, the economics of bioenergy utilization indicate that the applied technologies are not promising compared to conventional (fossil-based) energy, while environmental assessments have demonstrated bioenergy products (e.g., bio-oil, bio-fuel, and bio-jet fuel) can improve air and water quality. Therefore, utilization of bioenergy is expected to increase to accommodate environmental needs and pressures (McKendry, 2002), and proposed bioenergy technologies will need to be evaluated with regard to environmental impacts. Several criteria have been considered to evaluate environmental impacts of bioenergy production systems, e.g., net energy yield and CF. Net energy yield analysis has been used to measure the energy efficiency and sustainability of bioenergy from biomass (Schmer et al., 2008). CF analysis refers to the total amount of greenhouse gases (GHGs) emitted throughout the bioenergy production system, measured in mass of CO_2 equivalent (kg CO_2 eq.). Transportation contributes a significant amount of CF in biomass to bioenergy SCs (Lam et al., 2010). Since transforming WB to bio-oil at bio-refineries is novel, there is little literature focusing on environmental assessment of the existing production technologies and SCs. The environmental impact assessment method applied herein estimates the CF, including CO_2, CH_4, and N_2O emissions from WB collection, transportation, and refinery processing.

3. Application of the model

A hypothetical case for WB to bio-oil processing is presented below for a four-county region located in northwest Oregon. Actual harvesting data and available information in the literature have been used to assess the reasonableness of the mathematical model presented in the previous section.

3.1. Background and assumptions

Data for WB amount and harvesting area locations have been provided by the State of Oregon Department of Forestry (ODF, 2015). Data for three forest districts, i.e., Astoria, Tillamook, and Forest Grove obtained from ODF include timber sale harvest data, a GIS layer for 49 harvesting areas, and forest road and highway GIS layers. The GIS layers containing spatial information for counties located in Oregon are from the U.S. Bureau of Land Management (US BLM, 2013).

Non-merchantable products remaining at roadside in the forest after harvesting are considered as FHR, and defined as products that lack sufficient quality to be used for pulpwood. According to ODF, red alder, western hemlock, and Douglas-fir tree species are the primary timber species. Moisture content is assumed constant (45% MC, wet basis) for all FHR. The transport of FHR is assumed to be mass-limited. The three forest districts are scattered across four counties, i.e., Tillamook, Clatsop, Columbia, and Washington counties. No large scale bio-oil refineries are operating in Oregon, thus, it was decided that potential fixed bio-oil refinery sites would be located at the center of each county. Fig. 2 illustrates the distribution of harvesting areas and the initial location of FRs across the region.

The potential locations for MRs were decided based on the geographical distribution of harvesting areas scattered across the three forest districts. Therefore, one MR is located among the harvesting areas that are geographically closest to each other. Consequently, 16 MR locations were selected throughout the region to serve the harvest areas (Fig. 3). Biomass from each harvest area was assumed to be processed by the nearest MR. Since the time horizon applied in this study is one year, the capital and operational costs of FRs and MRs are dependent to two major factors: the expected operational life and the period of operation in a specific location. Due to its mobility, the latter factor is more appropriate for MRs. To determine annualized cost, the expected life of the MR was assumed to be 10 years (Page-Dumroese et al., 2009); the depreciated life has been considered same for the FR.

3.1.1. Description of mobile and fixed refineries

The capacity, operational cost, and capital cost of an MR were calculated with respect to the data developed by Mullaney et al. (2002) and Page-Dumroese et al. (2009). The annual operational cost for an MR was estimated using an empirical model (Eq. (33)), which is based on the linear interpolation of operational cost per year (C_{op_mob}) for different capacities (metric tons per day) of fixed refineries CAP_{fix}.

$$C_{op\_mob} = 7454.2 \cdot CAP_{fix} + 70,527 \tag{33}$$

The operational cost for FRs has been extracted from work by Mullaney et al. (2002). Attributes of both refineries considered in this application are summarized in Table 1.

The biomass storage cost was obtained from a study developed by Rentizelas et al. (2009) for a covered storage facility without
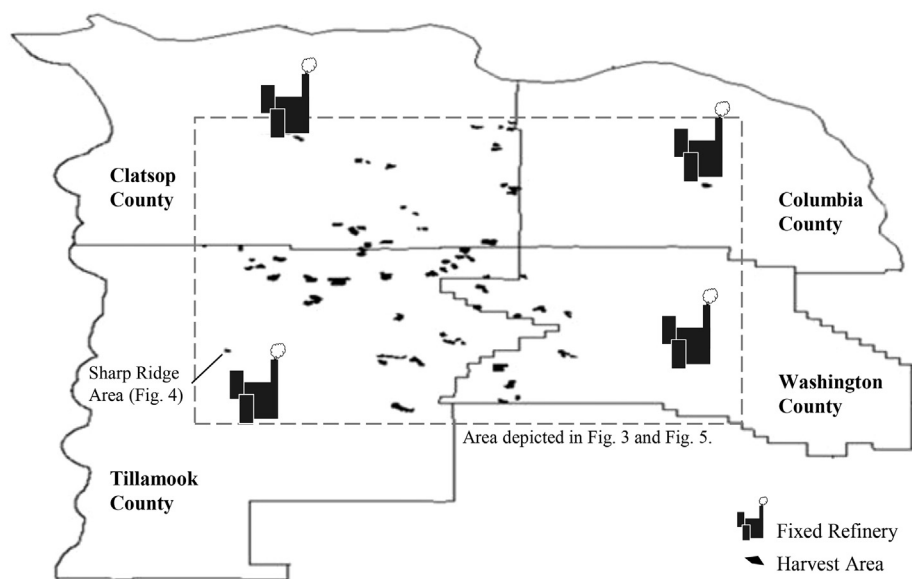
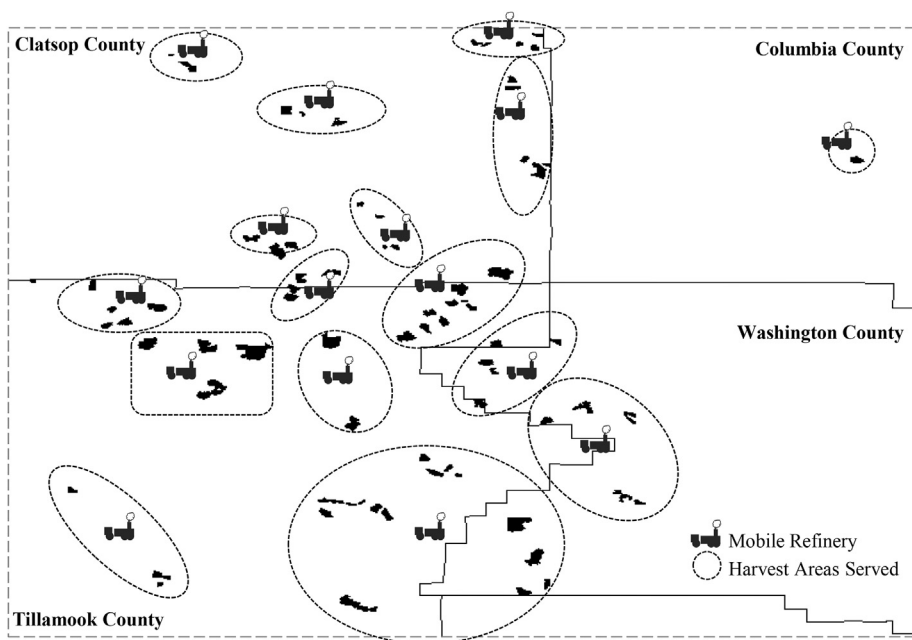**Fig. 2.** Distribution of harvesting areas and potential locations of fixed refineries.

Fig. 3. Distribution of mobile refineries among harvesting areas.

Table 1
Summary of mobile and fixed refinery attributes.

Attributes	Mobile	Fixed
Refinery size (metric tons per day, tpd)	13.6	363
Biomass (45% MC) processing rate (metric tons per year)	4950	132,000
Bio-oil production capacity (thousand liters per year)	1650	43,930
Refinery capital cost (US $)	1,584,890	15,396,680
Expected operational/depreciated life (years)	10	20
Refinery operational cost (US $ per year)	196,320	5,212,610
Biomass storage facility capital cost (US $)	–	732,550
Bio-oil storage facility capital cost (US $)	–	1,516,870
Bio-oil product yield (%)	50	50

drying infrastructure, which has a capital cost of $156/m^2$, adjusted for inflation to 2014 (BLS, 2015). It is assumed to have a square footprint (28 m per side) and a height of 6 m. Due to lack of information and for simplicity the flow of biomass is considered as just-in-time, thus, the transformation process begins as the batches of woody residue arrive at the refineries. As a result, inventory (holding) cost is not considered in this application. For bio-oil storage cost, two steel tanks, each with the capacity of about 28,600 m^3 (180,000 bbl.), are selected to be located next to an FR (B2-Consultants LLC, 2013). This capacity is assumed to accommodate the oil production of the FR, as well as that of MRs located throughout the surrounding region. Bio-oil from MRs is brought by the tankers to the storage facility locations prior to shipment, thus this storage is not limited only to the production of the harvest areas presented in this study. The processing cost per metric ton for both the FRs and MRs have been assumed to be same in this study.

The annual cost of an FR (C_{fix}) is calculated (Eq. (34)) as the summation of the capital cost of the refinery (C_{cap_fix}) divided by its expected operational life (K_{fix}) and the prorated operational cost, which is based on the operational cost (C_{op_fix}), the amount of biomass processed, and the annual processing rate (R_{ann_fix}). The annual cost of an MR (C_{mob} is calculated (Eq. (35)) by considering its prorated cost based on its annual processing rate (R_{ann_mob}), assuming the ability to serve multiple harvest areas throughout the year, the amount of biomass processed, operational costs (C_{op_mob}), and capital cost (C_{cap_mob}) divided by the expected operational life of the refinery (K_{mob}). The annual cost of a biomass storage facility (C_{st_mass}) is calculated (Eq. (36)) divided by the total capital and operational cost of storage (TC_{st_mass}) by the expected operational life of the biomass storage facility (K_{st_mass}). The annual cost of a bio-oil storage facility (C_{st_oil}) is calculated (Eq. (37)) by dividing the total capital and operational cost of storage (TC_{st_oil}) by the expected operational life of the bio-oil storage facility (K_{st_oil}).

$$C_{fix} = \frac{C_{cap\_fix}}{K_{fix}} + \sum_k \sum_l \sum_t X_{klt} * \left(C_{op\_fix} \right) \bigg/ R_{ann\_fix} \qquad (34)$$

$$C_{mob} = \left[\frac{C_{cap\_mob}}{K_{mob}} + C_{op\_mob} \right] \cdot \left[\sum_i \sum_j \sum_t X_{ijt} \bigg/ R_{ann\_mob} \right] \qquad (35)$$

$$C_{st\_mass} = TC_{st\_mass} / K_{st\_mass} \qquad (36)$$

$$C_{st\_oil} = TC_{st\_oil} / K_{st\_oil} \qquad (37)$$

3.1.2. Calculation of travel distance

The shortest path between harvesting areas and refineries and between the FRs and MRs is calculated by developing a road network in GIS software (ArcGIS 10). The road GIS layer provides two main categories of roads (forest roads and highways); all forest roads feed into highways. Fig. 4 depicts the path between one harvesting area (Sharp Ridge) and the FR located in Tillamook County. The distance from the nearest highway location to the refinery is assumed to be negligible.

3.1.3. Truck operating cost

The operating cost per mile varies with respect to the type of terrain traversed, as well as truck size. Straight frame hook-lift trucks can be used for biomass transport for in-forest roads, but they are primarily used for short distance delivery of WB due to
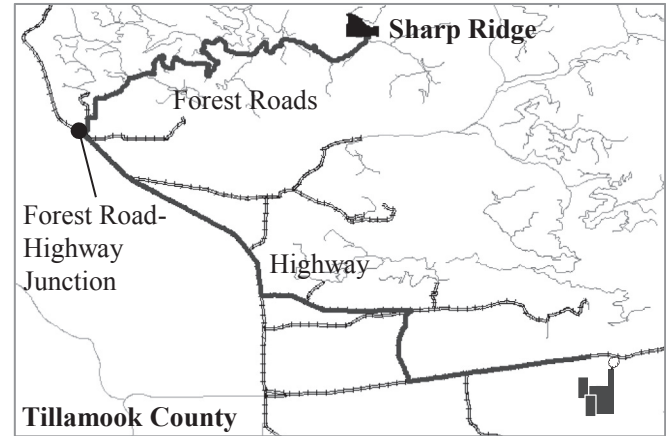

Fig. 4. Shortest path between the Sharp Ridge harvesting area and the fixed refinery located in Tillamook County.

their limited capacity. For longer distance transport, a trailer can be attached to double capacity. In the case of the additional trailer, the hook-lift truck shuttles bins between a hook-up point along an improved road and the in-forest site. This study used a hook-lift truck with capacity of 13.6 metric tons (15 U.S. tons) for hauling biomass on in-forest roads. If on-highway hauling is used, an additional trailer is added at the highway road junction, doubling capacity. The cost of hook-up and unhook-up cost is $120 per round trip. The capacity of tanker transport is assumed to be 18.2 metric tons (20 U.S. tons). The truck operating cost of $3.26 per mile ($2.02 per km) is adjusted for inflation to 2014, based on the value $2.98 per mile ($1.85 per km) reported by Mason et al. (2008), which includes wages and fixed and variable costs.

3.1.4. Calculation of carbon footprint

According to the U.S. Environmental Protection Agency (U.S. EPA), the CF for heavy and medium duty trucks is 0.298 kg CO_2 eq. per US ton-mile (0.328 kg CO_2 eq. per metric ton-mile) (U.S. EPA, 2008). According to Steele et al. (2012) the cradle-to-grave environmental impact of producing bio-oil is 0.0323 kg CO_2 eq. per MJ of bio-oil, and includes collection of biomass and the pyrolysis process.

4. Results and discussion

The results of the SC cost model are presented in this section for a base case and several alternative scenarios. Also, the environmental impact of SC alternatives is evaluated by assessing their CF, a key environmental performance indicator for bio-based energy SCs. The alternative scenarios are developed to assess the effect of model factors on predicted economic and environmental measures. The results for each scenario are also discussed.

4.1. Computational results

The mathematical model presented in Section 2 is solved through an optimization solver (Gurobi 5.6.3) along with Python 2.7 (Gurobi Optimization Inc., 2014; Van Rossum, 2007). The model has 2127 constraints, 28 binary variables, 1088 integer variables, and 1092 continuous non-negative variables. Gurobi solves the problem to optimality after 6786 simplex iterations and 9.12 s. For the case presented, with 16 potential mobile and four FR locations, the results indicate that the optimal SC would consist of 14 MRs that are located within all four counties. The MRs would be

responsible for processing WB from all harvesting areas except Modified Green, Grease Alder, and Mombo Combo, which are in Clatsop County.

The MR would process almost all of the WB available in the harvesting areas served. The total production for the region is estimated to be about 4,537,205 L (4537.2 m^3 or 1,198,733 gal.) of bio-oil. The optimal annual cost for the base case is calculated as $1,004,443 or $0.221/L ($0.84/gal.) by considering the transportation costs and annualized capital and operational costs for each facility. Table 2 reports key parameter values for the optimal solution for this base case.

Table 3 represents the estimated CF for the considered biomass collection, transportation, FRs and MRs for this case.

4.2. Sensitivity analysis

According to the framework of the model presented in Section 2, several factors can have a crucial effect on the economic and environmental performance of the SC. The purpose of the sensitivity analysis is to evaluate the effect of major factors on the base case results presented in Section 4.1, i.e., MR capital cost, operational life, and operational cost, available WB, and storage facility cost. Two cases, in addition to the base case, are considered for each factor and the cost and carbon footprint results for each case are compared (Table 4).

4.2.1. Effect of mobile refinery capital cost

The effects of MR capital cost and operational life are investigated in this section. In the first alternative scenario (Case 1), the capital cost of an MR has been decreased by 50% and in the second scenario (Case 2), the operational life of the refinery is increased by 10 years in addition to the capital cost reduction. These scenarios reflect MR technology improvement. According to the modeling results (Fig. 5), the optimal number and location of the FR and MR would remain the same compared to the base case with the changes explored for capital cost. The amount of WB processed by the MR increases in Case 1 and Case 2. The overall cost decreased by about $167,711 (17%), in Case 1, and by about $250,933 (30%) in Case 2. The CF remains constant in both cases since the location and number of refineries, along with the quantity of WB processed by each remains constant. The model indicates that the optimal location and environmental impact appear to be independent respectively to changes in the capital cost and operational life of the MRs.

4.2.2. Effect of mobile refinery operational cost

The effect of the operational cost of the MR on the overall SC cost is investigated by developing two scenarios. In the first (Case 3), the operational cost is increased by 50% and in the second scenario (Case 4), this cost is decreased by 50%. The optimal number and location of FRs and MRs have changed in Case 3. The amount of WB processed by each refinery remains constant. The overall cost of the system, however, changes directly as a function of the operational

Table 3
Environmental impact of transportation activities and refinery infrastructure.

Supply chain entity	Carbon footprint (Mg CO$_2$ eq.)
Transportation	168.5
Fixed refinery processing	–
Mobile refinery processing	4372.8
Biomass collection	102.2
Total	4643.5

cost of the MR (Fig. 6). Hence, the annual cost in Case 3 is increased by about $65,527 (6.5%) and the annual cost in Case 4 is reduced by $216,887 (21.6%). This analysis demonstrates that changes to the operational cost of the MR appear to have effect on the optimal SC configuration. In Case 3, the results indicate that the optimal SC would consist of an FR rather than MRs in the base case and the FRs would be responsible for processing WB from all harvesting areas. Conversely, in Case 4, the results of the analysis indicate that 14 MRs would be responsible for processing WB.

4.2.3. Effect of available woody biomass

The amount of WB considered in the base case was based on non-merchantable products remaining at roadside after thinning and final harvest processes. This source of woody residue is not the only feedstock source for the bio-oil process. Branches, tops, and breakage, not at roadside, can be another source of WB (forest slash), much of which would be piled and burned. According to ODF, roughly 2268–2722 metric tons (2500–3000 U.S. tons) are burned in each state forest zone. This amount is greater for private forests, equating to about 11,340–11,794 metric tons (12,500–13,000 U.S. tons) for each forest zone in this study. In the first scenario (Case 5), the state forest slash is added to the non-merchantable product to determine the mass of WB. It is assumed that 8165 metric tons (9000 U.S. tons) of slash and 2722 metric tons (3000 U.S. tons) slash per forest zone, are uniformly distributed among the 49 harvesting areas. In the second scenario (Case 6), privately-owned forest slash is added to the amount used in Case 5. This amount is calculated as 29,937 metric tons (33,000 U.S. tons) total and uniformly distributed among the 49 harvesting areas. Collection cost of slash is not considered. The results indicate that MRs would not be used in Case 5 and Case 6. With increased biomass, the annual cost increases by about $103,260 (10%) in Case 5 (Fig. 7).

This indicates increasing the volume of biomass leads to an increase in transportation costs, which are offset by elimination of capital and operating costs of the MR. In Case 6, the cost is increased by about $229,004 (23%), due to the additional trips necessary for WB transport. Commensurately, the CF increases by 1,476,205 kg CO$_2$ equivalent (32%) in Case 5 and by 6,367,912 kg CO$_2$ equivalent (137%) in Case 6.

4.2.4. Effect of storage facility cost

Two scenarios have been developed to evaluate the effect of storage facility capital costs on modeling results. In the first

Table 2
Parameter details for the optimal solution of the mathematical model for the base case.

Parameter description	Name	Value
Woody biomass transferred to the mobile refinery (metric tons)	X_{ijt}	10,886
Woody biomass transferred to the fixed refinery (metric tons)	X_{ikt}, X_{klt}	0
Number of in-forest truck trips	n_{ijt}	806
Number of highway truck trips	n_{klt}	0
Number of bio-oil tanker trips between mobile and fixed refineries	n_{jlt}	304
Bio-oil produced by the mobile refinery (metric tons)	Y_{jlt}	5443
Bio-oil produced by the fixed refinery (metric tons)	Y_{lct}	0

Table 4
Summary description of each case scenario.

Case	Objective	Description
Case 1	Effect of mobile refinery capital cost	Capital cost of a mobile refinery has been decreased by 50%
Case 2	Effect of mobile refinery capital cost	Operational life of the refinery is increased by 10 years
Case 3	Effect of mobile refinery operational cost	Operational cost is increased by 50%
Case 4	Effect of mobile refinery operational cost	Operational cost is decreased by 50%
Case 5	Effect of available woody biomass	7407 metric tons biomass added
Case 6	Effect of available woody biomass	27,158 metric tons added
Case 7	Effect of storage facility cost	Biomass and bio-oil storage cost is increased by 50%
Case 8	Effect of storage facility cost	Biomass and bio-oil storage cost is reduced by 50%
Case 9	Effect of mobile refinery locations	MRs are located 10 miles (16 km) farther away
Case 10	Effect of mobile refinery locations	MRs are located 30 miles (48.2 km) farther away
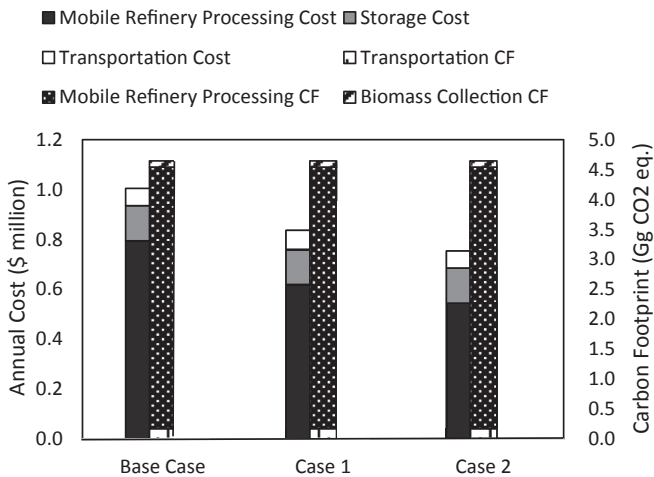
Fig. 5. Effect of mobile refinery capital cost on environmental and economic measures.
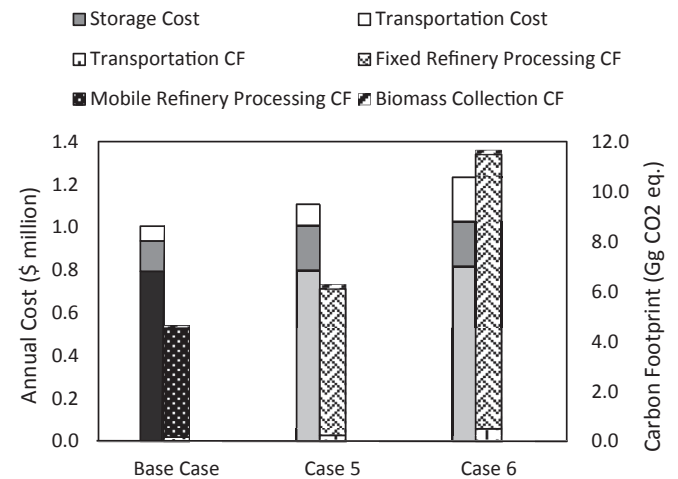
Fig. 7. Effect of available woody biomass on environmental and economic measures.
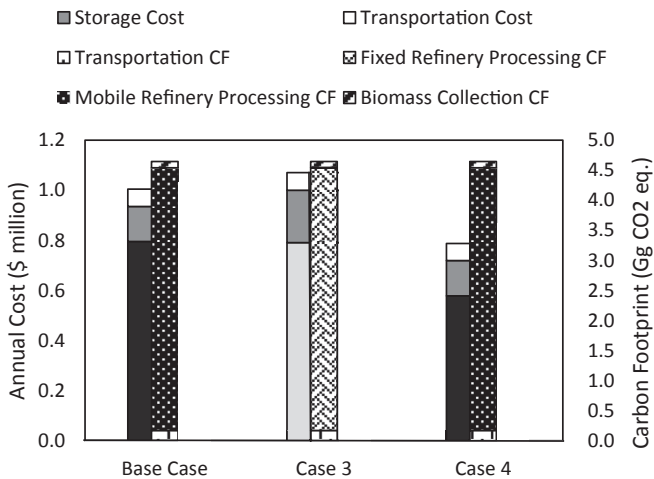
Fig. 6. Effect of mobile refinery operational cost on environmental and economic measures.
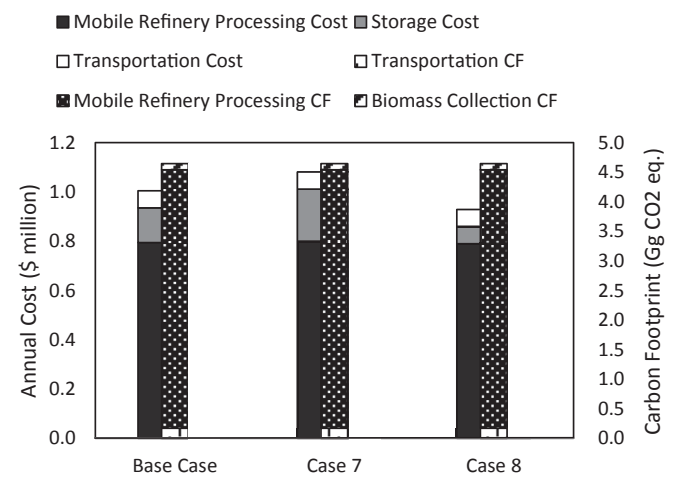
Fig. 8. Effect of storage cost on environmental and economic measures.

scenario (Case 7), the cost of establishing biomass and bio-oil storage is increased by 50% and in the second scenario (Case 8) these costs are reduced by 50%. The results show no change in the optimal combination refineries from the base case, nor in the amount of WB processed by the MR, and consequently, the CF (Fig. 8). The overall cost of the system, however, has a direct correlation with facility capital cost. The overall cost is increased by about $75,843 (7.5%) in Case 7 and is decreased by the same percentage in Case 8 ($75,843). The results show that the optimal

solution is not sensitive to the changes in the bio-oil and biomass storage costs.

4.2.5. Effect of mobile refinery locations

The impact of the distance of the MR from the forest, a primary factor in decision making, is investigated in this section. In the first scenario (Case 9), MRs are located 10 miles (16 km) farther than the original location. In the second scenario (Case 10), MRs are located at a distance of 30 miles (48.2 km) from the original locations, while holding all other parameters constant. The latter is farther than
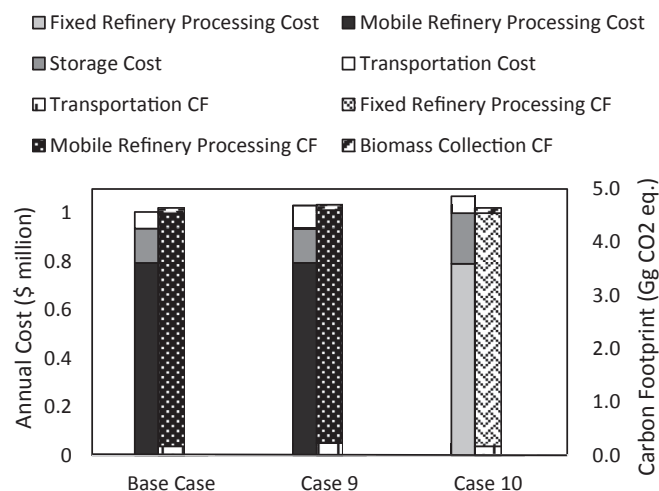
Fig. 9. Effect of mobile refinery location on environmental and economic measures.

would be realistic, but is used to evaluate sensitivity of the model. The overall SC cost and CF are found to be directly related to the distance (Fig. 9). The optimal number of the MRs remains constant in Case 9. When the distance increases to 30 miles (16 km), however, the results indicate that MRs would not be used and all WB would be processed with a single FR. Also, the total quantity of WB processed remains unchanged. The annual cost is increased by about $26,587 (2.6%) in Case 9 and by about $65,571 (6.5%) in Case 10. CF is increased by about 52,929 kg CO_2 eq. in Case 9 and is increased by 1677 kg CO_2 equivalent in Case 10.

5. Summary

An MILP mathematical model was developed to obtain the optimal combination of fixed and mobile bio-oil refinery facilities to serve a given forested region. The optimization model was demonstrated using an optimization solver (Gurobi 5.6.3) along with Python 2.7 to evaluate a set of three forest districts comprising 49 harvesting areas in northwestern Oregon. For a base case considering 16 mobile and four FR locations, the solver identified 12 MR locations. The amount of WB processed in the base case at the 12 selected refinery sites was 10,886 metric tons. The overall annual cost of the system, consisting of transportation, refinery (capital and operational), and storage costs, was calculated to be $1,004,443 or $0.221/L ($0.84/gal.) of bio-oil, adjusted for inflation to 2014. The environmental impact assessment estimated the CF of transportation and production of bio-oil. Transportation CF was determined using the U.S. EPA method (U.S. EPA, 2008), and CF of biomass collection and pyrolysis processing was based on work by Steele et al. (2012). The total annual CF for the base case was calculated to be about 4.643×10^6 Gg CO_2 eq., or 1.02 kg CO_2 eq./L. According to U.S. EIA (2015), the wholesale price of heating oil averaged $0.76/L ($2.91/gal.) in 2014, which is approximately 3.5 times higher than the calculated cost of bio-oil presented in this study. Additionally, the CF of crude oil production is 0.095 kg CO_2 eq./MJ (Unnasch et al., 2009), which is about three times higher than for bio-oil production.

Sensitivity analysis on modeling parameters was performed to estimate the effect of each factor on the results, including the SC configuration and associated cost and CF. The results of the sensitivity analysis indicated that operational cost of the MR, amount of WB, and transportation-related factors appeared to have a significant impact on the number and location of the facilities. As would

be expected, the overall cost of the system was found to be directly related to the capital cost of the storage facilities and the operational cost of the MR, i.e., as these costs increase, the overall cost of the system increases. Two scenarios were developed to examine the effect of changes in the MR capital cost to evaluate the impact of technology improvement. The results indicated that changes in MR capital cost had no impact on the optimal solution for the cases evaluated. Additionally, the location of the fixed facility was investigated to evaluate the effect of distance from the harvesting area on cost and CF modeling results. Table 5 indicates the total distances between each entity in base case, Case 3, Case 5, Case 6, Case 9, and Case 10. The analysis found that as distance between harvesting area and MR increases, the transportation cost will increase due to transferring more WB than bio-oil. Thus, adapting the role of new MR technology in the SC is more critical under long distance scenarios (e.g., increased in-forest truck capacities would aid in decreasing MR-related transportation costs). Further, the effect of distance on the amount of WB processed by the MR confirms the hypothesis that transportation activities greatly influence sustainability performance of the WB SC, measured by cost and CF.

Another factor examined in the sensitivity analysis was the available amount of WB. The available amount of WB was first increased by adding state in-forest slash to the non-merchantable product mass used in the base case (Case 5) and, in Case 6, by adding private and state forest slash to the base amount. The results showed that an increase in the volume of available WB led to an increase in transportation costs and CF. The solution also eliminated the MR and accepted higher transportation costs over the increased cost of MRs. Comparisons between the base case scenario and other scenarios in the sensitivity analysis are summarized in Table 6.

6. Conclusions

Earlier studies focused on upstream biomass to bioenergy SC cost considered harvesting/collection, logistics, and storage, while pretreatment was not investigated. Mirkouei et al. (under review) reviewed the literature in detail by examining the conventional upstream segment biomass-to-bioenergy SCs structure. The work presented here addresses two limitations of modeling and optimization of bio-energy SCs. First, while previous studies have focused on optimizing the SCs for producing other types of forest fuels, the cost model developed is the first reported that focuses on SC optimization for the use of in-forest WB for bio-oil production. Second, the mathematical model developed in this study is the first reported that optimizes an integrated SC for a combination of fixed and mobile bio-oil refineries. Finally, it is the first known study to simultaneously investigate economic and environmental impact measures for the bio-oil SC as indicators of sustainability performance.

In spite of the advances made in this work, there are limitations in the model that should be addressed by future research to

Table 5
Sum of round trip distances between each entity for different case scenarios.

	Forest to mobile refinery (km)	Mobile refinery to storage facility (km)	Forest to main road (km)	Main road to fixed refinery (km)
Base case[a]	29,914	25,691	—	—
Case 3	—	—	33,114	36,257
Case 5	—	—	56,846	80,778
Case 6	—	—	97,934	136,050
Case 9	56,510	403,823	—	—
Case 10	—	—	33,050	36,268

[a] Other cases not reported in the table are the same as the base case.

Table 6
Summary comparisons between different case scenarios.

Case	Total biomass (thousands of metric tons)	Total bio-oil (thousands of liters)	Total carbon footprint (Mg CO$_2$ eq.)	Total cost (thousands of dollars)	Unit cost ($/L)	Unit carbon footprint (kg CO$_2$ eq./L)
Base case	10.89	4536	4643	1004.4	0.22	1.02
Case 1	10.89	4536	4643	836.7	0.18	1.02
Case 2	10.89	4536	4643	753.5	0.17	1.02
Case 3	10.89	4536	4645	1069.9	0.24	1.02
Case 4	10.89	4536	4643	787.5	0.17	1.02
Case 5	18.29	7622	6270	1107.7	0.15	0.82
Case 6	38.04	15,851	11,661	1233.4	0.08	0.74
Case 7	10.89	4536	4643	1080.2	0.24	1.02
Case 8	10.89	4536	4643	928.6	0.20	1.02
Case 9	10.89	4536	4701	1031.0	0.23	1.04
Case 10	10.89	4536	4645	1070.0	0.24	1.02

improve the accuracy and relevance of results in the design of biomass SCs. The model was implemented in a non-dynamic case study, considering a one-year time period, which neglected the impact of dynamic changes, e.g., scheduling impacts due to weather, demand, and downtime, and the availability of trucks and processing equipment. Since timber harvesting varies by season, the time of year can have a significant impact on the overall cost, e.g., additional storage and inventory cost or more transportation activities in certain months of the year. Also, since distance-finding was done manually using GIS data to determine forest road and highway distances individually from two map layers, only routes from each harvest area to the nearest MRs were determined. Due to the manual method, MR locations were fixed, which inhibits optimization of refinery locations. Thus, if the MRs were not operating or had reached capacity, biomass would be transported to an FR, as opposed to the next nearest MR. Another limitation is related to the assumption of mass-limited biomass transport, which may be the case for high-density, non-merchantable product, but FHRs such as tops and limbs can widely vary in density, causing transport to be volume-limited. Thus, WB density can have a profound impact on the required number of trips from the harvesting area to the refinery.

The generalized mathematical model and assessment approach developed for evaluating the economic and environmental performance of bio-oil production SCs is complex, and the application to a relatively small geographic region demonstrated herein required many assumptions to simplify analysis and facilitate optimization using integer programming and a solver package. Evaluation of the system, however, was able to demonstrate insights into the factors that influence the SC configuration and associated costs and CFs. It is critical that mathematical approaches, such as that explored here, continue to be developed so informed system-level decisions can be made that will advance the development and implementation of robust and sustainable energy systems.

Acknowledgments

Annex A. Nomenclature

Indices

c	set of storage sites
fix	fixed bio-refinery
i	set of harvesting sites
in	inventory
j	set of mobile sites
k	set of main-road junctions
l	set of fixed refinery sites
mob	mobile bio-refinery
s	small tractor-trailer
st_mass	biomass storage
st_oil	bio-oil storage
t	time period
tnk	tanker trucks

Parameters

C_{cap_fix}	capital cost of fixed refinery (US $)
C_{cap_mob}	capital cost of mobile refinery (US $)
C_{fix}	annual cost of a fixed refinery (including capital and operational costs) (US $)
C_{in}	annual inventory cost of woody biomass ($/metric ton)
C_{mob}	annual cost of a mobile refinery (including capital and operational cost) (US $)
C_{op_fix}	operational cost of fixed refinery (US $)
C_{op_mob}	operational cost of mobile refinery (US $)
C_s	transportation cost of small in-forest tractor-trailer to mobile refinery (US $/mile)
C_{2s}	transportation cost of on-highway tractor-trailer to fixed refinery (US $/mile)
C_{st_mass}	annual cost of biomass storage at a fixed refinery (US $)
C_{st_oil}	annual cost of bio-oil storage at a fixed refinery (US $)
C_{tnk}	transportation cost of tanker trailer to fixed refinery (US $/mile)
CAP_{2s}	capacity of small tractor-trailer with two trailers (metric ton)
CAP_b	capacity of large tractor-trailer (metric ton)
CAP_{fix}	capacity of fixed refinery (metric ton)
CAP_{mob}	capacity of mobile refinery (metric ton)
CAP_m	capacity of medium tractor-trailer (metric ton)
CAP_s	capacity of small tractor-trailer (metric ton)
CAP_{st_mass}	capacity of biomass storage facility (metric ton)
CAP_{st_oil}	capacity of bio-oil storage facility (metric ton)
CAP_{tnk}	capacity of tanker truck (metric ton)
D_{ijt}	distance between a harvest site and a mobile refinery (miles)
D_{ikt}	distance between a harvest site and a main road junction (miles)
D_{klt}	distance between a main road junction and a fixed refinery (miles)
D_{jlt}	distance between a mobile refinery and a fixed refinery (miles)
K_{fix}	expected operational life of the fixed refinery (year)
K_{mob}	expected operational life of the mobile refinery (year)

K_{st_mass}	expected operational life of the biomass storage facility (year)
K_{st_oil}	expected operational life of the bio-oil storage facility (year)
M	large positive constant (Big M)
R_{ann_fix}	annual processing rate of fixed refinery (metric ton)
R_{ann_mob}	annual processing rate of mobile refinery (metric ton)
S	percentage yield
TC_{st_mass}	total capital and operational costs of biomass storage facility (US $)
TC_{st_oil}	total capital and operational costs of bio-oil storage facility (US $)
θ	the available amount of woody biomass in all harvesting sites (metric ton)

Continuous variables

X_{ijt}	amount of biomass from site i to site j at time t (metric ton)
X_{ikt}	amount of biomass from site i to site k at time t (metric ton)
X_{klt}	amount of biomass from site k to site l at time t (metric ton)
Y_{jlt}	amount of bio-oil from site j to site l at time t (metric ton)
Y_{lct}	amount of bio-oil from site l to site c at time t (metric ton)

Binary variables

α_{lt}	binary variable for fixed refinery at time t
β_{jt}	binary variable for mobile refinery at time t
γ_{lct}	binary variable for bio-oil storage at time t
δ_{lct}	binary variable for biomass storage at time t

Integer variables

n_{ijt}	number of in-forest tractor-trailer trips to transfer woody biomass form harvesting area to nearest mobile refinery at time t
n_{ikt}	number of in-forest tractor-trailer trips to transfer woody biomass from harvesting area to nearest main road junction at time t
n_{klt}	number of highway tractor-trailer trips to transfer woody biomass from main road junction to nearest fixed refinery at time t
n_{jlt}	number of tanker trailer trips to transfer bio-oil from mobile refinery to fixed refinery at time t

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