ECONOMIC ASSESSMENT AND OPTIMIZATION OF FOREST BIOMASS SUPPLY
CHAIN FOR HEAT GENERATION IN A DISTRICT HEATING SYSTEM

by

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Abstract

This research investigates the feasibility of exploiting local forest biomass for district heat generation in Williams Lake, BC. The objectives of this research are (1) to examine the economic viability of delivering forest biomass to the gate of a potential heating plant, and (2) to find a cost-optimized supply chain for delivering biomass to the plant. Considering the impact of biomass availability on the design of the supply chain and the required logistics in the system makes this study distinctive from the previous research.

To achieve the first objective, the annual total delivery cost of biomass to the plant, namely the material, handling, processing, and transportation costs, was calculated for supply chain options with and without terminal storages. The results of the feasibility study showed that depending on the distance of source points to the plant, the delivery cost of woodchips to the plant ranged from $2.19 \text{ GJ}^{-1}$ to $2.87 \text{ GJ}^{-1}$. However, the gap between supply and demand in some months indicated that the direct flow of woodchips from source points to the plant would not be always possible. To meet the demand in months with biomass shortage, forest biomass should be stored in a terminal storage although this could increase the total annual cost to $6.59 \text{ GJ}^{-1}$. At the same time, transferring all the plant’s demand via terminal storage would not seem economical since in the months with more supply than demand and also with good accessibility to the collection areas, the direct flow is possible.

Using a mix of direct and indirect flows might provide the opportunity to deliver forest biomass to the plant at a lower cost. A linear programming model was used to minimize the total annual cost and to determine the optimal flow of biomass to the heating plant. The optimization results revealed that the optimal flow of biomass would cost $2.62 \text{ GJ}^{-1}$, which is less expensive than the current delivery cost of natural gas to the plant ($6.39 \text{ GJ}^{-1}$). Therefore, the use of forest biomass for energy generation might be economical depending upon the capital and operating costs of the energy conversion facility.
Preface

The work on this thesis including literature review, contacting and consulting industry experts, data gathering, developing the costing and optimization models, running models, and analysing the results was carried out by the author, Shaghaygh Akhtari, with advising support provided by Dr. Taraneh Sowlati, the research supervisor. Dr. Sowlati, Mr. Ken Day, and I identified the research problem. The written work derived from this study was created by the author with comments from Dr. Sowlati and Mr. Day.

The method used for estimating the capacity of storage in Chapter 3 was adopted from Gronalt et al. (2007) and the optimization model used in Chapter 4 was adopted from Gunnarsson et al. (2004). These models, however, were modified based on the case study by the author.

A version of Chapter 3 has been submitted for publication. Akhtari S., Sowlati T., Day K., Feasibility of using regional forest biomass for generating district heat in Williams Lake.

A version of Chapter 2 (Optimization studies) has been submitted for publication. Shabani N., Akhtari S., Sowlati T., Deterministic and stochastic models in value chain optimization of forest biomass for bioenergy production: A review.

A version of the literature on techno-economic assessment of forest biomass utilization for energy generation in district energy systems in Chapter 2 is ready for submission. Akhtari S., Sowlati, T., Day k., Economic feasibility of utilizing forest biomass in district heating systems: A review.

A version of Chapter 4 is ready for submission: Akhtari S., Sowlati T., Day k., Optimal flow of forest biomass to a district heating system in Williams Lake, BC.
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To my mother, Zari,
and in memory of my father, Mansour,
with love and appreciation
Chapter 1. Introduction

1.1 Background

In recent years, energy providers have been seeking ways to overcome the issues raised by fossil fuel utilization for energy generation. Firstly, historical data show that fossil fuel prices have been experiencing a general upward trend over time (Figure 1.1). The prices are expected to continue rising in the long term future because of dwindling of fossil fuel resources as a consequence of soaring demand (Chea 2004).

Security of fossil fuel supplies is another aspect of concern about fossil fuel consumption (Globe Foundation 2007). Supply disruption might happen due to political instability in oil producing countries, weather conditions, and natural disasters (Johnson 2012). Furthermore, fossil fuels are non-renewable and at the current consumption rates meeting the global demand will be a challenge (Shafiee et al. 2009).

![Figure 1.1: Annual average fossil fuel prices](image)

Adopted from: EIA (2012)
Another issue is that fossil fuel combustion discharges CO₂ to the atmosphere and raises concerns about global warming and greenhouse gas effects. Producing and supplying energy contribute to approximately 80% of Canada’s greenhouse gas emissions of which a large share is emitted from fossil fuel combustion (Environment Canada 2012a).

Rising prices, insecurity of fuel supplies, and negative environmental impacts of burning fossil fuels urge corrective actions. Two major solutions have been approached: energy conservation and replacing fossil fuels by alternative energy sources (Globe Foundation 2007).

Energy conservation is achievable through reducing the use of conventional fuel sources via either replacing bulbs with fluorescents, replacing electric drying with air drying, and using power strips; or the use of more efficient energy generation methods (Energy Conservation 2012), e.g., district energy systems.

In district energy systems (DESs), a central plant generates thermal energy, heat and hot water, and a network of pipelines distributes the produced energy in the form of hot water or steam to a group of buildings in a community (CDEA 2009, Gilmour et al. 2007). Heat exchangers installed at each building draw off the heat from water. After circulating the heat within the interior atmosphere, a separate pipe network returns the water to the central plant for reheating (Schweig 1997). In addition to heat and hot water, district energy systems may provide chilled water. Recently, the simultaneous production of heat and power in a district energy system, called combined heat and power (CHP) system, has become possible using the cogeneration technology (Gilmour et al. 2007).

District heating systems provide higher efficiencies in comparison with decentralized systems, which produce and consume energy within the same building. For instance, the efficiency of a CHP system is 35-40% higher than the efficiency of a conventional power generation system (Gochenour 2001). As a consequence of higher efficiency, primary fuel consumption decreases and some negative environmental impacts of fuel burning might be offset. District heating systems can use a wide variety of fuels including fossil fuels and renewables and offer better pollution control than decentralized systems (Gochenour 2001).
Canada established its first DHS in London, Ontario in 1880. This district heating system served university, hospital and government buildings. In 1924, Winnipeg started Canada’s first commercial district energy system (CDEA 2011). Today, 118 district energy systems are in operation in Canada (CDEA 2009). Ontario has the highest number of district heating systems, 43%, followed by Alberta (12%), and British Columbia (10%), respectively (CDEA 2009). The majority of these heating systems operate on natural gas which is a well secured source of energy throughout the country (CDEA 2009).

Table 1-1 lists some operating district energy systems in British Columbia along with the heat sources and services they provide. The recent district energy systems are operating on renewable energy sources including wood residues, geothermal heat, and sewer heat, while most of these systems still use natural gas for their backup systems. Table 1-2 lists under construction and proposed district energy systems in British Columbia.

The other solution to overcome concerns about burning fossil fuels is to replace them with renewable sources of energy. Sun, wind, water, biomass, and geothermal heat are some sources of renewable energy. Renewables replenish naturally or by sustainable practices. They can be burned to generate heat and electricity directly or to produce biofuel liquids, such as ethanol or bio-diesel, which can be used as transportation fuel or combusted for heat and power production. Replacing fossil fuels with renewables can mitigate greenhouse gas emissions and improve air quality.

Renewable energy sources including moving water, biomass, wind, solar, geothermal, and ocean energy make up 16.5% of Canada’s primary energy supply (Nyboer et al. 2011). Moving water is the largest renewable source of energy that provides 60% of electricity in Canada (Nyboer et al. 2011). Biomass has the second largest share in renewable sources. The most important supplier of biomass in Canada is the forest industry (Nyboer et al. 2011). Landfill methane gas, biogas (gas produced during the decomposition of organic material), municipal solid wastes (MSW), and agricultural residues (used for bio-fuel production) are other types of biomass feedstock in Canada (Nyboer et al. 2011). Biomass feedstock compromises 6% of Canada’s total primary energy supply (Nyboer et al. 2011). Solar, earth and tidal energy are also other categories of renewable sources of energy in Canada experiencing rapid growth rates (Nyboer et al. 2011).
Table 1-1: Operating district energy systems in British Columbia  
Source: Ostergaard (2012)

<table>
<thead>
<tr>
<th>City</th>
<th>Operator</th>
<th>Heat source(s)</th>
<th>Service(s)</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burnaby</td>
<td>Simon Fraser University</td>
<td>Natural gas</td>
<td>Heat- Hot water</td>
<td>1966</td>
</tr>
<tr>
<td>Gibsons</td>
<td>Town of Gibsons</td>
<td>Geothermal</td>
<td>Heat- Cooling- Hot water</td>
<td>2011</td>
</tr>
<tr>
<td>Kamloops</td>
<td>Sun Rivers Resort</td>
<td>Geothermal- Natural gas</td>
<td>Heat- Cooling- Electricity</td>
<td>2010</td>
</tr>
<tr>
<td>Kelowna</td>
<td>Okanagan College</td>
<td>Natural gas- Sewage heat- Solar</td>
<td>Heat</td>
<td>2004</td>
</tr>
<tr>
<td></td>
<td>University of British Columbia- Okanagan</td>
<td>Natural gas- Geothermal- Solar</td>
<td>Heat- Cooling</td>
<td>2007</td>
</tr>
<tr>
<td>North Vancouver</td>
<td>Lonsdale Energy Corporation</td>
<td>Natural gas</td>
<td>Heat</td>
<td>2004</td>
</tr>
<tr>
<td>Prince George</td>
<td>University of Northern British Columbia</td>
<td>Wood residues- Natural gas</td>
<td>Heat- Hot water</td>
<td>2010</td>
</tr>
<tr>
<td></td>
<td>City Of Prince George (downtown)</td>
<td>Wood residues- Natural gas</td>
<td>Heat- Hot water</td>
<td>2012</td>
</tr>
<tr>
<td>Revelstoke</td>
<td>Revelstoke Community Energy Corp.</td>
<td>Wood residues</td>
<td>Heat</td>
<td>2005</td>
</tr>
<tr>
<td>Vancouver</td>
<td>Central Heat Distribution</td>
<td>Natural gas-Bio-methane</td>
<td>Heat</td>
<td>1968</td>
</tr>
<tr>
<td></td>
<td>Southeast False Creek/Olympic Village</td>
<td>Sewer heat- Natural gas</td>
<td>Heat- Hot water</td>
<td>2009</td>
</tr>
<tr>
<td></td>
<td>University of British Columbia</td>
<td>Natural gas</td>
<td>Heat</td>
<td>1925</td>
</tr>
<tr>
<td>Victoria</td>
<td>Dockside Green</td>
<td>Wood residues- Natural gas</td>
<td>Heat- Hot water</td>
<td>2009</td>
</tr>
<tr>
<td>Whistler</td>
<td>Whistler Athletes’ Village</td>
<td>Sewer heat- Natural gas</td>
<td>Heat- Hot water</td>
<td>2009</td>
</tr>
</tbody>
</table>
Table 1-2: Proposed and under construction district energy systems in British Columbia

Source: Ostergaard (2012)

<table>
<thead>
<tr>
<th>Under construction district energy systems</th>
<th>City</th>
<th>Operator</th>
<th>Heat source(s)</th>
<th>Service(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burnaby</td>
<td>Simon Fraser University</td>
<td>Wood residues- Natural gas</td>
<td>Heat- Hot water- Electricity</td>
<td></td>
</tr>
<tr>
<td>Richmond</td>
<td>The Alexander Energy Utility</td>
<td>Geothermal</td>
<td>Heat- Hot water- Cooling</td>
<td></td>
</tr>
<tr>
<td>Surrey</td>
<td>Surrey City Center</td>
<td>Geothermal</td>
<td>Heat- Hot water- Cooling</td>
<td></td>
</tr>
<tr>
<td>Vancouver</td>
<td>River District Energy System</td>
<td>Biomass- Natural gas</td>
<td>Heat- Hot water</td>
<td></td>
</tr>
<tr>
<td></td>
<td>UBC</td>
<td>Wood residues</td>
<td>Heat- Hot water</td>
<td></td>
</tr>
<tr>
<td>Proposed</td>
<td>Quesnel</td>
<td>Fortis Quesnel CHP System</td>
<td>Heat recovery- Natural gas</td>
<td>Hot water- Electricity</td>
</tr>
</tbody>
</table>

In British Columbia, renewable energy generation from biomass comes second (11.8%) after hydro electricity production (86.6%) (Nyboer et al. 2011). Since 60% of land (55 million hectares out of 90 million hectares) in British Columbia is forest land, forestry is the major supplier of biomass in the province (MOF 2003). Forest biomass broadly denotes wastes from milling, and residues from forestry practices: thinning and logging (Bradley 2007).

British Columbia has the largest volume of harvest in Canada (Bradley 2007) with an annual harvest volume of 77.3 million m³ (MOF 2012). Bradley (2007) reports that 20% to 40% of the total annual harvest is turned into wastes in British Columbia, while this percentage is 9% to 14% of the total annual harvest in the other provinces. The reason for higher residue ratio in British Columbia is the massive harvest of trees infested by mountain pine beetle in the province (Bradley 2007). It is estimated that an annual quantity of 11 million Odt of harvesting residues is left at the roadside in British Columbia (Bradley 2007).

British Columbia accounts for 43% of total lumber production in Canada (Bradley 2007). In 2004, the province produced 16,614 MMfbm\(^1\) of lumber and a total of 6,553,759\(^2\) Odt\(^3\) of

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1 One million board feet; one board foot is the volume of a board 1 foot long, 1 foot wide, and 1 inch thick.

2 This amount only denotes the residue production in the Interior British Columbia. Coastal residue production is negligible.
residues including bark, sawdust and shavings, of which 67% was consumed domestically, 5% was exported, and the rest (28%) was incinerated or disposed of in landfills (Bradley 2007). MOF (2011b) stated that 52% of the lumber mills’ log input was converted to waste including sawdust, shavings, and chips in British Columbia.

Using forest biomass for energy generation confronts some challenges; it is too costly to compete with conventional fossil fuels. Because of low energy content of biomass, large quantities of biomass should be purchased to generate a given output of energy compared to fossil fuels (Allen et al. 1998). To burn biomass in some boilers, e.g., pyrolysis (Mitchell et al. 1995), its moisture content needs to be reduced through drying or storage processes (Van Dyken et al. 2010). Biomass transportation cost is relatively high since its low bulk density necessitates a large number of trucks to deliver biomass to the heating plant (Allen et al. 1998, Caputo et al. 2005). Moreover, biomass is dispersed over a large area and to collect a significant quantity of biomass large distances should be covered (Caputo et al. 2005). Biomass availability fluctuates seasonally and to fulfill the demand in seasons with biomass shortage biomass should be stored in terminal storages (Kanzian et al. 2009). In summary, despite its environmental advantage, forest biomass may not be able to compete with fossil fuels in terms of delivery cost because of its complex supply chain (Stockinger et al. 1998). Thus, before making any investments, it is important to estimate the biomass supply chain costs.

Several studies calculated the cost of energy generation from forest biomass using different conversion technologies (Schneider et al. 2000, Broek et al. 2001, Nicholls et al. 2002, Caputo et al. 2005, and Fischer et al. 2011), while some other studies compared the cost of electricity generation from different energy resources. Kumar et al. (2003) made a comparison between the cost of energy generation from forest biomass and agricultural residues. Broek et al. (2001) and Gan et al. (2006) compared coal and forest biomass for energy generation. In all of these studies, the delivery cost of biomass to the gate of energy plants was expressed as the fuel cost. None of them broke the total cost into its different cost components. Gautam et al. (2010) calculated the cost of felling, skidding, loading, chipping, and transportation of wildfire burnt trees to a

\[^{3}\text{Odt (Oven dry tonne): the amount of biomass that weighs 2000 lbs at zero moisture content.}\]
combined heat and power plant in Ontario. However, the authors only considered an annual direct flow of biomass to the CHP system. Because of the seasonality of available biomass and heat demand, it is not always possible to fulfill the demand through direct flow. Thus, terminal storages are required to buffer the gap between supply and demand. Terminal storages increase the delivery cost of biomass feedstock to the energy plants. Therefore, it is essential to assess the impact of fluctuations in biomass availability and heat demand on the design of the supply chain and on the economics of supply chains with terminal storages. In the present study, the impact of variability in biomass availability during the year on the design of the supply chain, logistics of the supply chain, and total delivery cost of biomass to the plant has been taken into account as a determining factor to estimate the delivery cost of forest biomass.

An economic assessment study provides the estimates of the delivery cost of biomass to the energy conversion points or energy generation costs from biomass; however, the costs estimated in an economic assessment study might not be the lowest possible. That is why many authors used mathematical programming as a means to find the optimal delivery cost of biomass or the optimal cost of energy generation from biomass. Eriksson et al. (1989), Gunnarsson et al. (2004), and Kanzian et al. (2009) developed optimization models to minimize the delivery cost of forest biomass to the gate of energy plants while making decisions about the flow of forest biomass (direct or via storage) to the plants. Freppaz et al. (2004), Frombo et al. (2009a), and Alam et al. (2010) maximized the profit of energy generation from forest biomass. One common decision in all of these studies was to find the optimal flow of biomass from different supply areas.

1.2 Research objectives

This research pursues two main objectives:

(1) Economic feasibility of utilizing forest biomass for generating heat in a district heating system in Williams Lake, BC. This objective is achievable through:
1. Quantifying the monthly heat demand of the district heating system
2. Quantifying the monthly availability of local forest biomass
3. Identifying supply chain options to deliver forest biomass to the gate of the plant
4. Calculating the delivery cost of forest biomass to the gate of the plant using each supply chain option. The delivery cost of forest biomass denotes the costs that are occurred till the gate of the plant (The energy conversion costs at the plant are not taken into account).

(2) Optimization of forest biomass supply chain to the gate of the heating plant. To achieve this objective a linear mathematical model is developed. The results of the first objective are used as input data for this model to find an optimal flow of forest biomass from source points to the heating plant.

1.3 Case study

The city of Williams Lake (area: 33.03 km\(^2\) population: 11,150) is located in British Columbia Interior in the central part of the Cariboo region (The City of Williams Lake 2012b). Since Williams Lake is a hub for forestry activities (The City of Williams Lake 2012a), a considerable amount of wood residue is produced annually which is often open-burned or disposed of in landfills. The emissions and smoke from open-burning contain hazardous air pollutants and have adversely impacted the air quality and increased the CO\(_2\) emissions in the region (Bhattacharyya 1988). The City of Williams Lake is now considering using available regional biomass for energy generation as a means to improve the local air quality and mitigate its emissions (The City of Williams Lake 2011b). Figure 1.2 illustrates the emission changes between 2008 and 2010 and shows the anticipated emission trends from 2010 to 2020 in Williams Lake, BC.

The City’s target is to mitigate the CO\(_2\) emissions to 33% below the 2008 level, 709 tons of CO\(_2\) equivalents, by 2020 (The City of Williams Lake 2011a). The variations in the emission levels from 2008 to 2010 are attributed to changes in weather conditions and also emission reduction efforts. In order to meet the emission reduction targets, The City of Williams Lake has several plans (i.e. establishing a district heating system) which are in their early stages and will take place in near future (The City of Williams Lake 2011a).
This work focuses on a district heating system that fulfills the space heat demand and hot water requirements of five institutional and commercial buildings clustered in downtown core of Williams Lake. Table 1-3 lists these buildings along with their total natural gas and hydro consumption in 2008.

The locations for the district heating system and a loading-unloading site were suggested by Day (Personal communication on Feb 3-2012). Table 1-4 illustrates the coordinates of these locations.

Table 1-3: Secondary energy use in various buildings in Williams Lake, BC—2008
Source: Madrigga (Personal communication on Feb 16-2012)

<table>
<thead>
<tr>
<th>Building</th>
<th>Energy use (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Natural gas</td>
</tr>
<tr>
<td>RCMP Detachment</td>
<td>624</td>
</tr>
<tr>
<td>Williams Lake Senior Secondary School</td>
<td>11,000</td>
</tr>
<tr>
<td>Cariboo Memorial Hospital</td>
<td>28,578</td>
</tr>
<tr>
<td>Cariboo Memorial Complex Pool</td>
<td>6,156</td>
</tr>
<tr>
<td>Cariboo Memorial Complex Arena</td>
<td>5,990</td>
</tr>
<tr>
<td>Total</td>
<td>52,348</td>
</tr>
</tbody>
</table>
Several woody biomass sources are available to fuel the district heating system including harvesting residues, wastes from sawmills, wastes from interface fuel treatments, small scale logging on woodlots and private lands, wood wastes received at landfills, wastes from small timber sales, wood wastes from construction and demolition, and wastes from street and park maintenance. In this study, only two of above mentioned sources are investigated: wastes from small sawmills, and logging residues. It should be noted that the residues considered herein are not committed to any other industry in the region.

The sawmill considered as fuel providers in this study are selected from the operating sawmills in Central Cariboo region\(^4\) based on the following criteria: (1) sawmills should be reliable; herein, 5-year consecutive production from 2007 to 2011 determines the reliability of the supplier, (2) the residues should not be committed to other industries in the region, and (3) the sawmill should be located within an economic distance from the plant. The major domestic consumer of sawmill residues is Atlantic Power with the annual woodchips demand of 380,000 Odt\(^5\) of hog-fuel (NRCan and FPAC 2005). NRCan and FPAC (2005) suggested an economic haulage distance of 200 km for wood residues in Western Canada. However, since the economic distance is 100 km for Atlantic Power in Williams Lake (Watson- Personal communication on Nov 18-2012), this work uses a 100 km radius. Table 1-5 includes the list of sawmills that could provide residues to the plant and their locations.

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\(^4\)The information about sawmills including scale site and location in the region is available at http://www.docstoc.com/docs/34293861/Provincial-Scale-Site-List---BC-Government-Home---Province-of

\(^5\)Odt (Oven dry tonne) : the amount of biomass that weighs 2000 lbs. at 0% moisture content
Kehbila (2010) estimated the moisture content and bulk density of the Interior British Columbia’s sawmills’ by-products including chips, sawdust, shavings, bark, and trim ends. Moisture content of sawmill residues in the interior British Columbia averages about 30.52%. The average heat value and bulk density are 18.3 GJ.tonne⁻¹ and 215.29 kg.m⁻³.

Two logging sites, Gavin Lake block and Knife Creek Block of UBC Alex Fraser Research Forest, are investigated here as suppliers of logging residues to the plant.

Table 1-6 includes the location and the distance of logging sites to the potential heat plant and terminal storage.

---

### Table 1-6: Logging blocks and their geographic coordinates

<table>
<thead>
<tr>
<th>Location</th>
<th>Coordinates</th>
<th>Distance from (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Latitude</td>
<td>Longitude</td>
</tr>
<tr>
<td>Gavin Lake</td>
<td>52° 27'18.38&quot;N</td>
<td>121°44'45.57&quot;W</td>
</tr>
<tr>
<td>Knife Creak</td>
<td>52° 2'48.86&quot;N</td>
<td>121°50'12.18&quot;W</td>
</tr>
</tbody>
</table>

---

6 Weighted average is calculated after the quantity of sawmill residues has been estimated and broken down into the by-products.

7 Distances in Table 1-4, Table 1-5, and Table 1-6 are determined using Google Earth.
The average moisture content, heating value, and bulk density of logging residues in Williams Lake are 29.6%, 19.5 GJ.tonne\(^{-1}\), and 215.41 kg.m\(^{-3}\) (Jafari Naimi et al. 2009).\(^8\)

1.4 Thesis structure

The thesis is organized as follows:

(1) Chapter 2 provides a review of world literature on techno-economic assessment of using forest biomass for district energy generation and also reviews mathematical models developed to achieve an optimal solution to produce forest biomass based district energy. This chapter identifies the determining factors in feasibility of exploiting forest biomass for energy generation purposes.

(2) The feasibility of using forest biomass for generating district heat is investigated in Chapter 3. In this chapter, the heat demand of the district heating system is quantified, the quantity of biomass available for heat generation is estimated, and the cost of delivering biomass to the gate of the district heating systems is calculated when biomass is transported directly from the source points to the plant or when the biomass is transferred to the plant via a terminal storage.

(3) Chapter 4 presents a linear optimization model to find the optimal monthly flow of biomass to the heating plant such that the delivery cost of biomass to the heating plant is the minimum possible.

(4) Chapter 5 contains concluding remarks, limitations, and suggested future work.

\(^8\) The data from the case study 3 of this study are adopted herein.
Chapter 2. Literature review

2.1 Synopsis

This chapter begins with introducing technical solutions for converting biomass into a useful form of energy (Section 2.2). The focus of this section is on the conversion technologies that are suitable for generating heat and power from forest biomass. These technologies are combustion, gasification, and pyrolysis.

Then, Section 2.3 reviews the papers on the techno-economic assessment of forest biomass based district energy systems. Most of these studies have calculated the total cost of energy generation from forest biomass including delivering cost of biomass to the energy plant and costs incurred at the plant. A few papers focused only on the supply chain of forest biomass to the plant gate.

In Section 2.4, mathematical programming models developed to find an optimal solution for generating district energy are reviewed. Similar to the papers on techno-economic energy assessment, some of the papers considered the total energy generation from biomass. The objective function in these papers was to maximize the profit of energy generation from forest biomass including the delivered cost of biomass, conversion costs, and revenues from sale of energy. Some other papers only included the supply chain of biomass to plants. The objective of these studies was to minimize the delivery cost of biomass feedstock to energy plants.

Finally, the conclusions of the global literature reviewed in this chapter are presented in Section 2.5.

2.2 Conversion technologies

Converting the potential energy content of biomass into useful forms of energy is achievable through various technical processes. Figure 2.1 summarizes these processes and their products schematically.

This section focuses on only thermo-chemical processes—combustion, gasification, and pyrolysis—since heat and electricity are main products of these processes and they are frequently used for generating district heat and electricity. Chemical and bio-chemical technologies are used
for alcohol production through fermentation and methane-enriched gas production through anaerobic digestion (EPA 2007). These liquid products are usually consumed in transportation sector and also in engines and turbine electrical power generators as fuel (UNF 2008).

Figure 2.1: Biomass conversion processes and their products
Combustion

Direct combustion is the most developed process for generating energy from biomass. In combustion, biomass is burned in the presence of excess amount of oxygen and produces hot gases of 800-1000°C (McKendry 2002). The released gases can be either used directly for heating purposes or introduced into a steam turbine for generating electricity (Kehbila 2010). Combustion technologies are commercially available in a wide range of capacities from 2 kW for domestic heating to 500 MW for industrial purposes (Preto 2010) with typical boiler efficiency ranging from 50 percent to 90 percent based on higher heating value\(^9\) (Quaak et al. 1999). Higher conversion efficiencies are achieved in large scale power plants (100 MWe) or when biomass is co-fired with fossil fuels (Baxter et al. 2011). The moisture content of biomass feedstock should be less than 50% (wb\(^{10}\)); however, any type of biomass can be used in combustion (McKendry 2002). Fixed bed, fluidized bed and pulverized technologies are prominent types of combustion systems with variety within each group. In the fixed bed combustion technology, the biomass is fed into a fixed bed (grate) and the primary air is blown from below. Then, produced combustible gases start burning when additional air is injected into the combustion zone (Van Loo et al. 2007). Fixed bed systems include grate furnaces and underfeed stokers. Grate furnaces are suitable for capacities higher than 20 MW and biomass feedstock with high moisture and ash content. Underfeed stokers are best suited for small and medium capacities up to 6 MWth (Knoef 2003). The fluidized bed combustion system is mostly used for combusting municipal and industrial waste. Silica sand and dolomite are the bed material commonly used. The primary air is blown to the mixture of bed material and biomass feedstock. A low amount of secondary air is required for the combustion to be completed. Fluidized bed systems are more suitable for capacities larger than 30 MWth (Van Loo et al. 2007). In pulverized combustion, primary combustion takes place when fuel and combustion air are mixed, and then injected to the burning chamber. The combustion process ends when the secondary air is injected. This type of

\(^9\) The higher heating value of a fuel refers to the amount of heat released from the complete combustion of a unit quantity of a fuel when all the combustion products are cooled down to the pre-combustion temperature and all the vapor products are condensed.

\(^{10}\) wb: wet basis moisture content which expresses the ratio of moisture mass to the total mass.
combustion is suitable for very small particle size of biomass (average diameters smaller than 2 mm), e.g., wood dust. Moisture content should be less than 20% (wb) (Van Loo et. al 2007).

In generating electricity through biomass combustion, only one third of fuel energy can be converted into electricity (UNF 2008). Combined heat and power (CHP) generation is the way to increase the conversion efficiency. In CHP processes, exhausted steam from electricity generation turbines is recovered and used in order to meet process heat requirements (UNF 2008).

- Gasification

In gasification, the amount of oxidizing agent (air, oxygen, or steam) is limited and controlled carefully in a way that only a portion of biomass feedstock is burnt completely. The oxidizing agent determines the products of the gasification process (Bridgwater 1995). A gasification process in the presence of steam (indirect gasification) generates producer gas—a mixture of CO, H₂, CO₂, and CH₄. Due to its poor quality (higher heating value of 4-7 MJ.m⁻³), producer gas is not suitable for pipeline transmission, but it can be used in engine and turbines (Bridgwater 1995). If gasification takes place in the presence of limited amount of oxygen or air (direct gasification) instead of steam, synthetic gas—a mixture of CO, H₂, and N₂—is produced. The higher heating value of synthetic gas (10-18 MJ.m⁻³) makes it suitable for limited pipeline transmission and also for conversion to methanol and gasoline. Ash, char, oil, and tar are other products of gasification (Bridgwater 1995).

Fixed bed and fluidized bed gasifiers are the principal types of gasification systems with variations within each type. Fixed bed gasifiers operate at temperatures around 1000 °C and are more suitable for biomass particle size of 3 to 5 mm. Updraft and downdraft gasifiers are within this category and they are different in terms of the direction of flow of the gas and feedstock. When the feedstock is fuelled into the reactor from the top and oxidation agent is blown from the bottom, the gasifier is updraft. In downdraft gasification, the biomass and air or steam enter the reactor at the same direction and from the top part, but the combustible gases are withdrawn to the bottom part. For particle sizes of 5-7 mm, fluidized bed gasification is more appropriate. Operating temperature in these gasifiers are around 700-900 °C and due to being isothermal,
these gasifiers have higher efficiencies than fixed bed gasifiers (five times). Bubbling fluidized bed and circulating fluidized bed are different types of fluidized bed gasifiers (McKendry 2002, Bridgwater 1995).

Biomass integrated gasification combined cycle (BIGCC) has been used to generate medium scaled combined heat and electricity. This technology is known to be very efficient and environmentally friendly since the gas is cleaned before being directed into the turbine. In this cycle, the primary power is generated in a gas-fired turbine and the exhausted heat from the turbine is used to produce high pressure heat. This high pressure heat is then used to drive a steam turbine and secondary power is generated (McKendry 2002).

- **Pyrolysis**

Pyrolysis decomposes biomass in the absence of oxygen. The initial stages of pyrolysis start at 200 °C and it completes at 400-600 °C. Bio-oil, char, and non-condensable gases are the products of pyrolysis; however the distribution of these products can vary based on the applied temperature and vapor residence time. Low process temperature and long residence time favors the production of charcoal, while higher temperatures and lower hot vapor residence time favors the production of liquid (Bridgwater 2007). Figure 2.2 shows different pyrolysis processes with their product distribution. Pyrolysis is known to be suitable for fine particles (less than 3 mm particle size) with moisture content less than 10%. The char and gas produced in pyrolysis can be used within the process for meeting heat requirements.
2.3 Techno-economic assessment of using forest biomass for district energy generation

Similar to any other engineering project, the economic feasibility of district heating systems should be investigated. This section provides a review of literature on techno-economic assessment of using forest biomass for district energy generation. The studies are reviewed in two categories: (1) studies that focus on energy generation cost from biomass and (2) studies that focus only on the delivering cost of biomass to energy plants.

(1) Techno-economic assessment of district energy generation from forest biomass

Mitchell et al. (1995) calculated the cost of generating electricity using different conversion technologies: biomass integrated gasification combined cycle (BIGCC), pyrolysis, gasification, and combustion. The electricity generation cost included the delivered biomass cost, investment cost, and energy conversion costs amortized over the service life of the system. The authors concluded that the tradeoff between conversion efficiency and capital determined the most economical option. Although the IGCC and the pyrolysis systems were more efficient than the gasification alternative, the cost of generating electricity was the least in gasification. High capital cost of IGCC and pyrolysis systems outweighed the cost savings, i.e., savings in
material cost due to their high efficiencies. The combustion system was the least expensive system to acquire; however, its low efficiency resulted in higher biomass feedstock demand and consequently higher transportation cost than other options. The authors stated that using feedstock with lower moisture content in pyrolysis required less drying, therefore, it reduced the cost of generating electricity from this technology.

The impact of scale merit or economy of scale on the energy generation cost was considered in Schneider et al. (2000). The authors drew comparisons among the levelized cost of heat generation from thinning wastes and short rotation forestry residues through grate firing combustion in a 40 kW decentralized heating system, a 1000 kW district heating plant, and a 2500 kW district heating plant. Their results indicated that the larger was the system, the less expensive was the heat production. To determine the feasibility of forest biomass based heat generation, Schneider et al. (2000) compared the cost of electricity generation from forest biomass with that from solar energy, geothermal heat, and fossil fuels. Regardless of the size of system, heat generation from fossil fuels was always the least expensive option; however, heat from forest biomass was the least expensive renewable option. The authors discussed that governmental grants and subsidies along with taxes on CO₂ emissions could make biomass competitive with fossil fuels for heat generation.

Feasibility of large scale (1GWe) electricity production from short rotation crops in Spain was examined by Varela et al. (2001). Taking into account the minimum capacity of 15 MW for each power plant, a total of 28 power stations were identified to be needed to generate 1GWe, 22 fluidized bed combustion (FBC) plants and 6 biomass integrated gasification combined cycle (BIGCC) plants. This work revealed that BIGCC systems always produced less expensive electricity than FBC systems. Since BIGCC was a novel technology at the time of this study, Varela et al. (2001) expected considerable cost reduction in electricity generation using this system when more and more of them would be installed. Considering all the plants, the fuel cost had the largest share in the average electricity cost followed by investment cost, and operation and maintenance cost, respectively.

Broek et al. (2001) evaluated the possibility of small scale electricity generation in a 100 kW combined heat and power (CHP) from forest residues and sawdust in Ireland. The levelized cost
of electricity generated in this system was higher than the consumer price of electricity. The calculations in this study highlighted that although co-firing of biomass with coal or peat in existing power plants increased the cost of electricity generation in these plants, the electricity generation cost would be lower than electricity generated from forest residue in a CHP system.

Payback period and internal rate of return (IRR) of a small scaled (4-MM-BTUs-per-hour [1.17 MWh]) biomass district heating system were measured in Nicholls et al. (2002). Results revealed that low wood fuel costs, low wood moisture content and high alternative fuel costs had shorter payback period and higher IRR. The fuel cost impacted the profitability of the project more than the moisture content.

Straw from wheat and barley, harvesting residues, and whole forest trees were the focus in a study by Kumar et al. (2003) in Western Canada. These sources were ranked based on the levelized cost of electricity: (1) whole forest trees (the least expensive option), (2) straw, and (3) harvesting residues (the most expensive option). Yield per hectare was a determining factor in this ranking. High transportation cost due to the very low yield of harvesting residue placed this source in the third place with a considerable difference with straw in the second position. Straw had a lower yield than whole forest trees, but good access to the road offset a part of transportation cost, and thus the electricity cost from whole forest trees and straw were close. Kumar et al. (2003) stated that electricity generation using biomass was not economical in Western Canada. Introducing greenhouse gas credit might turn biomass based electricity generation economical, though.

Caputo et al. (2005) used net present value (NPV) to compare combustion and gasification systems. Although the gasification system was more efficient and had lower operating cost, at any production scale, the combustion system had higher NPV than the gasification system. This emphasized the higher impact of capital investment than that of operating costs in total economic performance of these systems. Positive NPVs were achieved for capacities larger than 25 MW for combustion system and larger than 30 MW for gasification system.

In their study, Gan et al. (2006) compared the cost of electricity generation from woody biomass including logging residues and poplar plantations with that of coal using a 100 MW biomass
gasification combined cycle, a 400 MW pulverized coal system and a 428 MW integrated coal gasification combined cycle. The electricity generation from woody biomass in biomass gasification combined cycle cost twice as high as two other systems. The authors stated that Imposing CO₂ emission taxes would increase the coal price and this would help biomass to be competitive with coal for electricity generation.

Dwivedi et al. (2009) calculated the average net present value of electricity generation from different types of energy plantations using gasification as conversion technology. In this work, the average NPV was negative, even when a total saving of $25 tonne⁻¹ was considered due to the elimination of carbon dioxide emissions. The authors argued that at the interest rate of 8%, the investment in the 100 kW gasifier would be feasible if the government would provide 50% of the cost of the gasification unit and civil works, and 100% of the distribution network establishment cost, and the electricity purchase price would increase by 37.5% from its current level.

Fischer et al. (2011) compared the levelized cost of electricity generation in 10 kW biomass and diesel gasification systems. The authors stated that the electricity from biomass could be cost competitive with electricity from diesel for higher capacity factors¹¹ than current ones. They also referred to a better economic performance of a 30 kW gasification system than a 10 kW gasifier.

Sawmill wastes, logging and thinning residues were the primary fuels for generating heat and power in a small scale gasification CHP plant in a study by Yagi et al. (2011). Considering the current stage of technology, sales price of electricity, and production cost of biomass fuel, only energy generation from sawmill wastes were feasible in this study. However, for lower prices of biomass production, logging residues might become feasible to be used if the gasification entered the commercialized stage. Thinning residues appeared not to be an economic source in this case because of high thinning cost.

¹¹ The capacity factor of a plant is the actual energy output of the plant over a given time period divided by the nominal capacity of the plant.
Rodriguez et al. (2011) evaluated the feasibility of electricity generation from agricultural residues (crop stubble) and forestry residues (harvesting and sawmill residues) by calculating the levelized cost of electricity generation. In their work, the cost of generating electricity from crop stubbles and forestry was higher than that from coal. The cost of biomass was distinguished as an important contributing factor to this infeasibility. Low bulk density of crop stubble would result in high delivery cost of biomass to the plant. Although found to be expensive, Renewable Energy Certificates (RECs) in Australia have turned the biomass utilization into an economically viable option for small scale electricity generation (less than 50 MW).

Table 2-1 summarized the papers reviewed in this section on economic assessment of using forest biomass for energy generation in district heating systems.
### Table 2-1: Summary of papers on techno-economic assessment of district energy generation from forest biomass

<table>
<thead>
<tr>
<th>Author/ Year/ Region</th>
<th>Conversion technology</th>
<th>Biomass feedstock</th>
<th>Method</th>
<th>Cost components</th>
</tr>
</thead>
</table>
| Mitchell et al. (1995) USA | Comparing 20 MWe:  
- BIGCC¹  
- Pyrolysis  
- Gasification  
- Combustion | • Logging residues  
- Short rotation coppice residues | Levelized cost of electricity ($/KWh):  
Interest rate: 10%  
Inflation rate: 5%  
Service life: 20 years | • Delivery cost of biomass  
• O&M costs |
| |   |   |        |   |
| Key findings: Gasification system generated the least expensive electricity. IGCC and pyrolysis systems had higher conversion efficiencies and required less material to be bought than IGCC; however, their high investment cost made them uneconomical to be adopted. The conversion efficiency of the combustion system was that low that material cost outweighed the low capital cost. |

| Schneider et al. (2000) Germany | Comparing combustion systems:  
- 40 kW  
- 1000 kW  
- 2500 kW | Comparing:  
- Thinning residues  
- Solar energy  
- Geothermal heat | Levelized cost of electricity (€/GJ):  
Interest rate: 4%  
Service life: 15 years |   |
| Key findings: |   |   | Feedstock production cost  
- Transportation cost  
- Investment cost  
- O&M costs |
|   |   |   |   |
| Varela et al. (2001) Spain | Comparing:  
- FBC2 (22 plants)  
- BIGCC1 (6 plants) | Poplar trees | Levelized cost of electricity (€/GJ):  
Interest rate: 5%  
Service life: 30 years |   |
| Key findings: |   |   | Delivery cost of biomass  
- Investment cost  
- Land cost  
- O&M costs |

¹ BIGCC: biomass integrated gasification combined cycle  
² FBC: fluidized bed combustion
<table>
<thead>
<tr>
<th>Author/ Year/ Region</th>
<th>Conversion technology</th>
<th>Biomass feedstock</th>
<th>Method</th>
<th>Cost components</th>
</tr>
</thead>
</table>
| Broek et al. (2001)  | CHP<sup>3</sup> (100 kW) | • Forest residues  
                     • Sawmill wastes | Levelized cost of electricity (€.GJ<sup>-1</sup>):  
Interest rate: 5%  
Service life: 25 years | • Fuel cost  
• Investment cost  
• O&M costs |
| Nicholls et al. (2002) | Combustion (4-MMBTU.h<sup>-1</sup>)<sup>4</sup> | • Mountain pine  
beetled wood  
• Sawmill wastes | • Internal rate of return  
• Payback period  
Interest rate: 7%  
Inflation rate: 4% for first 10 years, 7% for the second 10 years  
Service life: 20 years | • Biomass delivery cost  
• System capital cost  
• O&M costs |
| Kumar et al. (2003)  | Combustion | Comparing:  
• Straw  
• harvesting residues  
• whole trees | Levelized cost of electricity ($ .MWh<sup>-1</sup>):  
Interest rate: 10%  
Service life: 30 years | • Biomass cost  
• Transportation cost  
• Investment cost  
• Operating costs |

**Key findings:** Small scale electricity generation in the CHP system was more expensive than the current sale price of electricity. Co-firing of biomass with peat or coal in existing electricity plants would result in considerable cost reductions in electricity generation.

**Key findings:** Low wood fuel prices, low moisture content, and high alternative fuel cost were resulted in shorter payback period and greater rate of return. Fuel cost had the largest impact on the profitability of the project.

**Key findings:** None of the biomass sources generated electricity economically. Though, the least expensive biomass source to generate energy from was whole forest trees, followed by straw and harvesting residues. Biomass yield per hectare was a determining factor in this ranking. Introducing greenhouse gas credits might turn biomass based power generation economical.

---

<sup>3</sup> CHP: combined heat and power  
<sup>4</sup>MM-BTUs: one million British thermal unit (BTU)
Table 2-1: Cont. Summary of papers on techno-economic assessment of district energy generation from forest biomass

<table>
<thead>
<tr>
<th>Author/ Year/ Region</th>
<th>Conversion technology</th>
<th>Biomass feedstock</th>
<th>Method</th>
<th>Cost components</th>
</tr>
</thead>
</table>
| Caputo et al. (2005) Italy | Comparing (5-50 MWe) | Forest biomass in general | Net present value (NPV) (€) | • Investment cost  
• Operating costs  
• Logistics costs  
• Revenue from sale of energy |
|                      | • Combustion  
• Gasification |                   | Interest rate: 9% Service life: 20 years | |
|                      |                      |                   | |
| Key findings: Regardless of the system capacity, generating electricity in the combustion system was always less expensive. Low operating cost of the gasification system could not offset its high capital cost. Regardless of the conversion technology, larger systems had a better NPV. |
| Gan et al. (2006) USA | Comparing | • Pulverized coal (400 MWe)  
• Coal IGCC\(^1\) (428 MWe)  
• Biomass IGCC\(^1\) (100 MWe) | Levelized cost of electricity (€. GJ\(^{-1}\))  
Interest rate: 6.5% Service life: 20 years | • Delivered cost of biomass  
• Investment cost  
• O&M costs |
|                      | • Poplar trees  
• Logging residues |                   | |
| Key findings: Electricity generation in biomass IGCC system cost approximately twice as high as electricity generation cost in coal systems. Imposing tax on \(\text{CO}_2\) emissions would increase biomass utilization for electricity production. |
| Dwivedi et al. (2009) India | Gasification (100 kW) | Energy plantations | Net present value (NPV) ($)  
Interest rate: 8% Service life: 15 years | • Fuel cost  
• Investment cost  
• Transportation cost  
• Operating costs  
• Transmission and distribution cost |
|                      |                      |                   | |
| Key findings: NPV was always negative even when carbon credits were included in the economic analysis. In order to make it feasible, subsidies from government to cover capital costs were essential. |
Table 2-1: Cont. Summary of papers on techno-economic assessment of district energy generation from forest biomass

<table>
<thead>
<tr>
<th>Author/ Year/ Region</th>
<th>Conversion technology</th>
<th>Biomass feedstock</th>
<th>Method</th>
<th>Cost components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fischer et al. (2011) Vanuatu</td>
<td>Comparing • 10 kWe • 30 kWe Gasification systems</td>
<td>Comparing: • Energy trees • Diesel</td>
<td>Levelized cost of electricity ($.kWh⁻¹): Interest rate:10% Service life:20</td>
<td>• Investment cost • Fuel cost • Labor cost • O&amp;M costs</td>
</tr>
<tr>
<td>Yagi et al. (2011) Japan</td>
<td>CHP³ (&lt; 300 kWe)</td>
<td>Comparing • Sawmill • Logging • Thinning residues</td>
<td>Levelized cost of electricity ($.kWh⁻¹): Interest rate: not discussed Service life: not discussed</td>
<td>• Fuel cost • Investment cost • Transportation cost • O&amp;M costs</td>
</tr>
<tr>
<td>Rodriguez et al. (2011) Australia</td>
<td>Direct combustion (5 MW)</td>
<td>Comparing • Crop stubbles • Harvesting and sawmill residues</td>
<td>Levelized cost of electricity ($.kWh⁻¹): Interest rate:7.5% Service life: 30 years</td>
<td>• Fuel cost • Investment cost • O&amp;M costs</td>
</tr>
</tbody>
</table>

**Key findings:** Higher capacity factors than current ones made electricity from forest biomass cost competitive with electricity from diesel. Regardless of fuel type, the 30 kW gasification system had always better economic performance than the 10 kW system.

**Key findings:** Electricity generation from sawmill residues was already economical. Logging residue utilization for electricity generation would become feasible if biomass price would reduce and the investment cost of gasification would decrease. Thinning residues were never economical to use because of high thinning cost.

**Key findings:** In general electricity from forest residues was less expensive than agricultural residues. Electricity from both biomass sources was more expensive than from coal. However, renewable energy certificates in Australia has turned it feasible to generate energy from biomass.
(2) Techno-economic assessment of forest biomass supply chain to energy plants

The cost of electricity from agricultural residues including wheat straw and corn stover, and forestry residues including wastes from silvicultural operations were compared in a study by Ćosić et al. (2011). In this study, the best energy source depended on the electricity generation system. In the 10 MW plant, forest residues provided the least expensive electricity followed by wheat straw and corn stover, respectively, while in the 1 MW plant, the cost of generating electricity was the lowest for wheat straw followed by corn stover and forest residues, respectively. Ćosić et al. (2011) showed that biomass cost had a larger impact on electricity cost than transportation cost.

Delivering cost of wildfire burnt pine trees to the gate of a 67 MW biomass CHP plant in Ontario, Canada was calculated in Gautam et al. (2010). The supply chain included forwarding full-trees to roadside, grinding at roadside, and transporting to the plant. The annual equivalent procurement cost was estimated taking felling, extraction, grinding, and transportation costs into account. The results showed that of the total procurement costs, felling was the most expensive process with 36% contribution, and grinding was the least expensive one with 19% contribution. The low contribution of grinding cost in this research in comparison to similar studies was because of using an efficient grinder. The authors argued that although transportation cost was not considerable in their study, for longer distances it could be of great concern.

Yoshioka et al. (2011) selected among logging residues, trees from broad-leaf forest and trees from thinning operation to produce electricity in a 3 MW electricity plant. The results showed that logging residues were the least expensive source for this purpose since they were by-products of logging operations, e.g., limbing and bucking, and the calculated cost only included chipping and transportation costs. Broad leaf trees were less expensive than coniferous thinned trees because of their higher bulk density. In this work, technical improvement in logistics, e.g., introducing bundlers for densification was regarded as an important factor in order to decrease costs.

Table 2-2 includes the summary of papers reviewed on the economic assessment of forest biomass supply chain for district energy generation.
Table 2-2: Summary of papers on economic assessment of forest biomass supply chain

<table>
<thead>
<tr>
<th>Author/ Year/ Region</th>
<th>Conversion technology</th>
<th>Biomass feedstock</th>
<th>Method</th>
<th>Cost components</th>
</tr>
</thead>
</table>
| Gautam et al. (2010) Canada | CHP\(^1\) plant (67 MW) | Wildfire burned trees | Per unit delivery cost of biomass ($\cdot$GMT\(^{-1}\)):
Interest rate: 6%
Service life: 5 years | • Felling cost
• Collecting cost
• Grinding cost
• Transportation cost |

**Key findings:** The most and least expensive activities in the supply chain of biomass to the gate of plant were felling and grinding, respectively. The authors also emphasized on the considerable impact of transportation cost on total delivery cost of feedstock when plant was located in farther distance to the collection area than their case.

| Yoshioka et al. (2011) Japan | Power plant (3 MW) | Comparing:
• Logging residues
• Thinned trees
• Broad leaved trees | Per unit cost of electricity ($\cdot$Mg\(^{-1}\)):
Interest rate: not applicable
Service life: not applicable | • Harvesting cost
• Forwarding cost
• Transportation cost |

**Key findings:** None of the biomass resources was economical to be used for power production. Logging residues though were less expensive than two other biomass resources. Advancement in harvesting and bundling technologies might reduce the delivery cost of feedstock to the plant.

| Ćosić et al. (2011) Croatia | Grate combustion (1 MWe and 10 MWe) | Comparing:
• Wheat straw
• Corn stover
• Forest residues | Levelized cost of electricity ($\cdot$MWh\(^{-1}\)):
Interest rate: 18%
Service life: 12 years | • Biomass cost
• Transportation cost |

**Key findings:** In the 10 MW plant, forest residues provided the least expensive electricity followed by wheat straw and corn stover, respectively, while in the 1 MW plant, the cost of generating electricity was the lowest for wheat straw followed by corn stover and forest residues, respectively.

\(^1\)CHP: combined heat and power
2.4 Optimization

As explained earlier, one reason that forest biomass is expensive is its complex supply chain. Before utilization, biomass has to be chipped and reduced in size. Deciding where to comminute biomass can considerably affect the total cost of delivering biomass. Therefore, an important decision to make is where to comminute residues: at the landing, at terminals, or at plants. Also, inaccessibility of forest lands in some months and seasonal variation of forest biomass and demand urges including storage in the supply chain of forest biomass. Storage might improve the quality of forest fuel, but at the same time, the cost savings resulted from better fuel quality might not offset the increases in the transportation and storage costs. Finding the optimal flow of biomass from buffer storages to energy plants while minimizing the supply cost has been of great interest in the available literature.

One of the premier studies using mathematical programming in the operation of district energy systems was done by Eriksson et al. (1989). They used linear programming to make the following decisions: whether to transport biomass to the heating plant directly or via storage, and whether to chip biomass at roadside or at plant. The optimal solutions in this study were to chip residues at roadside and transport chips directly to the heating plant. When storage was used, additional transportation costs were incurred. The authors mentioned that this additional transportation cost would not be paid off by the improved quality (better moisture content) of biomass after storage.

A more complex situation with several storages and heating plants in the supply chain could be dealt with decision support systems (DSSs) as implemented in Gunnarsson et al. (2004). The objective of this mixed integer based DSS was to minimize the delivery cost of biomass to heating plants. The DSS defined the optimal location for chipping forest residues, at roadside or at terminal storage, and an optimal monthly plan for material flow in the supply chain, flow of non-chipped residues from roadsides to terminals and wood chips from roadside to the terminals or plants, from terminals to heating plants, and also from sawmills to storages or plants.

The supply chain in Kanzian et al. (2009) included 16 combined heat and power plants and 8 terminal storages. They presented an optimization model to minimize the biomass supply cost to
the plants including chipping, storing, and transportation costs while defining the optimal flow of wood chips. The results in this study were in line with Eriksson et al.’s results (1989); direct flow of biomass was less expensive.

The mixed integer programming model in a study by Keirstead et al. (2012) found the optimum cost of forest biomass supply for fulfilling the heat demand of an urban area. The decision regarding the biomass type in this optimization model was between importing wood chips and forest residues from nearby area. When the decision was to import forest residues, the chipping process was carried out within the studied area. The objective function in this study was to minimize the annual cost including the annual cost of fuel, biomass storage, transportation, and conversion costs.

Cost of energy generation is not limited to delivery cost of biomass. A significant determining factor in energy generation cost from forest biomass is the conversion technology. Investment, installation, pre-treatment, operation and maintenance, and labor costs differ for various types of technology solutions. Furthermore, conversion technologies are different in terms of their efficiency which dictates the amount of biomass required and affects the transportation cost. The cost advantage of larger systems, known as economy of scale, is a known fact. However, larger systems require more forest fuel and consequently need more raw material and have higher transportation cost.

Using mixed integer programming, Nagel (2000) selected between a co-generation system and an individual system for energy generation in Germany. Investment cost, fixed and variable costs, fuel cost, waste disposal cost and revenue from sale of energy (heat and/or electricity) were the components of the objective function of a mixed integer programming model. The author concluded that 22% of the total heat demand could be economically supplied by a biomass fired boiler for consumers with heat demand higher than 100 kW and the rest of demand should be supplied by an oil-fired boiler.

Usually, an optimization model can be used to make decision about different variables at the same time such as location, capacity, material flow, etc.
To decide whether to produce electricity in addition to heat at biomass combustion plants was studied in Freppaz et al. (2004). Their model’s objective function was to maximize the financial yield of six proposed plants, while deciding about the annual amount of biomass harvested in each collection area, the annual flow of biomass from each collection area to each plant, the percentages of heat and electricity generation in each plant and the capacity of combustion system in each plant.

Similar to Freppaz et al.’s work (2004), Frombo et al. (2009a) developed a mathematical programming model to find the optimal flow of biomass from collection areas to a heating plant and to decide about the operating capacity of the plant. They ran their linear model for different conversion technologies including grate firing combustion (GFC), fluidized bed combustion (FBC), fluidized bed gasification (FBG), and fast pyrolysis (FP). They compared the value of objective functions for each technology. The authors concluded that despite the low efficiency of grate firing combustion, it was the best technology to be adopted because of its lower installation and management cost compared to other alternative technologies. Frombo et al. (2009b) changed their model to a mixed integer programming to find the optimal conversion technology in an integrated model.

To optimize the supply chain of energy plants, it is sometimes necessary to formulate a problem with more than one objective since single objective models cannot always represent the problem faced. The objectives are often in conflict (minimizing and maximizing objectives) and it might not be possible to achieve an optimal solution that optimizes all the objectives simultaneously. In this situation, the trade-off between objectives can be shown and most efficient solution is selected.

Alam et al. (2010) constructed a three–objective model for optimizing the amount of each individual type of biomass from each of harvesting zones, and then applied their model to a 50 MW biomass power plant using both harvesting residues and poplar trees collected from three management zones as feedstock in North Western Ontario, Canada. Pre-emptive goal programming was applied to give priorities to the objectives: minimizing the procurement cost of feedstock (first priority), minimizing the transportation distance of biomass to the plant, and minimizing the feedstock moisture content.
Table 2-3 and Table 2-4 includes the summary of papers on optimization of forest biomass supply chain and papers on optimization of district energy generation from forest biomass.

Table 2-3: Summary of papers on optimization of forest biomass supply chain

<table>
<thead>
<tr>
<th>Author/ Year/ Region</th>
<th>Objective function</th>
<th>Decision variables</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eriksson et al. (1989) Sweden</td>
<td>Minimizing supply cost of forest biomass&lt;br&gt;• Chipping cost&lt;br&gt;• Storing cost&lt;br&gt;• Transportation cost</td>
<td>• Direct flow of biomass or via storage&lt;br&gt;• Chipping location</td>
<td>Linear Programming (LP)</td>
</tr>
<tr>
<td>Gunnarsson et al. (2004) Sweden</td>
<td>Minimizing biomass supply cost&lt;br&gt;• Transportation cost&lt;br&gt;• Chipping cost&lt;br&gt;• Storage cost</td>
<td>• Flow of biomass within the supply network&lt;br&gt;• Quality of biomass chipped and stored at roadside and terminal&lt;br&gt;• If biomass is forwarded to each roadside location or not (Binary variables)&lt;br&gt;• If biomass is chipped at each roadside location or not (Binary variable)&lt;br&gt;• If each sawmill is contracted or not (Binary variables)&lt;br&gt;• If each terminal is used or not (Binary variables)</td>
<td>Mixed Integer Programming (MIP)</td>
</tr>
<tr>
<td>Kanzian et al. (2009) Austria</td>
<td>Minimizing biomass supply cost to the heating plants&lt;br&gt;• Chipping cost&lt;br&gt;• Storing cost&lt;br&gt;• Transportation cost</td>
<td>• Volume of wood chips transported from each terminal to each plant&lt;br&gt;• To select among potential terminals and plants (Binary variable)</td>
<td>Mixed Linear Programming (MIP)</td>
</tr>
<tr>
<td>Keirstead et al. (2012) UK</td>
<td>Minimizing system cost&lt;br&gt;• Biomass cost&lt;br&gt;• Biomass storage cost&lt;br&gt;• Transportation cost&lt;br&gt;• Conversion costs</td>
<td>• Optimal capacity of boilers&lt;br&gt;• Whether chipped forest biomass should be imported from neighboring area or non-chipped residues should be imported and then chipped within the area (Binary variable)</td>
<td>Mixed Integer Programming (MIP)</td>
</tr>
<tr>
<td>Author/ Year/ Region</td>
<td>Objective function</td>
<td>Decision variables</td>
<td>Method</td>
</tr>
<tr>
<td>----------------------</td>
<td>--------------------</td>
<td>--------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Nagel (2000) Germany</td>
<td>Maximizing annual profit • Investment cost • Fixed and variable costs • Fuel cost • Waste disposal cost • Revenue from sale of energy</td>
<td>• Heat produced by each boiler at each time period • The capacity of the system • If a boiler would integrate to the heating system or not (Binary variable)</td>
<td>Mixed Integer Programming (MIP)</td>
</tr>
<tr>
<td>Freppaz et al. (2004) Italy</td>
<td>Maximizing annual profit • Harvesting cost • Transportation cost • Installation and maintenance costs • Energy distribution cost • Revenues from sale of energy</td>
<td>• Annual quantity of biomass harvested at each collection area • Annual quantity of biomass transported from each collection area to each of six district energy systems • Capacity of each plant • The percentage of thermal energy generated at each plant • If the plant produces electricity or not (Binary variable)</td>
<td>Mixed Integer Programming (MIP)</td>
</tr>
<tr>
<td>Frombo et al. (2009a) Italy</td>
<td>Maximizing net annual profit • Felling and processing costs • Skidding cost • Highway transportation cost • Plant installation and management costs • Revenue from sale of energy</td>
<td>• Annual quantity of biomass harvested from each supply area • The plant capacity for different conversion technologies including: GFC\textsuperscript{1}, FBC\textsuperscript{2}, FBG\textsuperscript{3}, and FP\textsuperscript{4}</td>
<td>Linear Programming (LP)</td>
</tr>
<tr>
<td>Frombo et al. (2009b) Italy</td>
<td>Maximizing net annual profit • Felling and processing costs • Skidding cost • Highway transportation cost • Plant installation and management costs • Revenue from sale of energy</td>
<td>• The quantity of biomass harvested at each harvesting location and to be used at each plant location. • The capacity of each plant • To select optimal conversion technology among GFC\textsuperscript{1}, FBC\textsuperscript{2}, FBG\textsuperscript{3}, and FP\textsuperscript{4} (Binary variables)</td>
<td>Mixed Integer Programming (MIP)</td>
</tr>
</tbody>
</table>
Table 2–4: Cont. Summary of papers on optimization of energy generation from forest biomass

<table>
<thead>
<tr>
<th>Author/ Year/ Region</th>
<th>Objective function</th>
<th>Decision variables</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Alam et al. (2010)</strong>&lt;br&gt;Canada</td>
<td>(1) Minimizing total biomass procurement cost&lt;br&gt;(2) Minimizing total distance for procurement of biomass&lt;br&gt;(3) Maximizing the quality of biomass (minimizing moisture content)</td>
<td>• Quantity of biomass procured from each supply location to each plant&lt;br&gt;• Biomass procurement zone selection (Binary variable)</td>
<td>Multi-Objective Programming</td>
</tr>
</tbody>
</table>

1 GFC: grate firing combustion
2 FBC: fluidized bed combustion
3 FBG: fluidized bed gasification
4 FP: fast pyrolysis
2.5 Discussion and conclusions

(1) Feasibility of using forest biomass for district energy generation

Reviewing previous literature revealed many common findings between them. The most important parameters that can affect the economic feasibility of investing in forest biomass district energy systems are summarized below:

**Biomass feedstock** can impact the economic performance of a district energy system in various ways. The availability of biomass limits the capacity of the plant (Allen et al. 1998). The purchase price of biomass was found to be a significant cost component by Schneider et al. (2000), Nicholls et al. (2002), Rodriguez et al. (2011), and Yagi et al. (2011). The yield per hectare of biomass was also known as an influential factor by Mitchell et al. (1995) and Kumar et al. (2003). The biomass with higher yield per hectare requires less truck movements to be collected from different collection areas, thus the transportation cost would be less than biomass with lower yield per hectare. Also, the transportation cost is less for biomass with higher bulk density. This was covered by Rodriguez et al. (2011) and Yoshioka et al. (2011). More wood can be transported within the same truck when bulk density is higher. Mitchell et al. (1995) referred to moisture content as an important factor particularly for technologies that require very low moisture content, e.g. pyrolysis. Lower pretreatment cost would be a cost advantage in this case.

**Procurement cost of biomass** includes harvesting, collecting, transportation of biomass to forest road and finally to the plant. Since these activities can account for more than 50 percent of forest fuel supply Allen et al. (1998), the related costs are very influential in economic viability of using forest biomass. The supply cost of forest biomass was referred to as an influential factor by Ćosić et al. (2011), Sedjo (1997), and Ahtikoski et al. (2008). However, some studies focused exclusively on transportation costs. Caputo et al. (2005) and Gautam et al. (2010) highlighted the importance of transportation costs. The improvement in efficiency of collection technologies were recognized to be associated to lower costs of energy generation by Yoshioka et al. (2011).

**Conversion technology** can affect the feasibility of using forest biomass for district energy generation. The operating scale of energy plant is an important factor. Larger plants show cost
advantage over smaller ones since the specific capital cost decreases as systems get larger. However, larger capacities do not necessarily guarantee less expensive energy generation. Large scale plants need more biomass to be purchased and collected from farther distances, which impose higher transportation cost to the system. Furthermore, as it was discussed previously the capacity of biomass plant is limited to the amount of available biomass (Caputo et al. 2005, Dwivedi et al. 2009, and Fischer et al. 2011).

Efficiency of a conversion technology can influence the feasibility. The higher the efficiency is, the less the amount of purchased biomass would be. The less the amount of required biomass, the less the transportation cost would be. Varela et al. (2001) discussed that using a more efficient technology could generate more electricity. However, Mitchell et al. (1995) and Caputo et al. (2005) showed that the cost savings due to higher efficiencies of these systems may not offset their higher capital cost.

Using novel technologies was found to be less attractive in district energy plants. The drawbacks of these systems are high capital cost and high labour cost (Bridgwater et al. 2002). Varela et al. (2001), Bridgwater et al. (2002) and Yagi et al. (2011) recognized that energy generation using novel technologies would cost too much, however they emphasized that learning and gaining experience would reduce the costs in the future.

**Policies and government incentives** have a key role in promoting and encouraging more investments in biomass district energy systems. Introducing CO₂ taxes and tradable carbon credits were regarded as policies that would encourage investments in biomass district energy systems by Sedjo (1997), Schneider et al. (2000), Kumar et al. (2003), Gan et al. (2006), and Kinoshita et al. (2010). The experience in Australia in setting up tradable carbon credit can be used by other countries. Rodriguez et al. (2011) showed that this policy in Australia has improved the energy generation using local biomass. However, policies that can enhance the share of biomass in energy generation are not limited to financial ones. Kinoshita et al. (2010) referred to lengthening the rotation period of trees as an important factor in making biomass profitable to be used in energy generation market in Japan. Schneider et al. (2000) and Dwivedi et al. (2009) argued that subsidies and grants would be essential to make biomass district energy systems of their studies profitable. Löfstedt (1996) mentioned that government subsidies have
been the most important factor in the success of Sweden to fulfill a major part of heat demand using biomass district energy systems.

(2) Optimization of district energy generation from forest biomass

The mathematical programming models reviewed in this research chapter emphasized the significance of the parameters found to be important in feasibility review section.

The selection of the conversion technology is an important decision to be made. Is it economical to generate energy in a district system or a decentralized energy system generates more profit? Nagel's mixed integer model (2000) answered this question for a case in Germany. Freppaz et al. (2004) developed a mixed integer model to find the optimal capacity of the plants knowing that combustion was the proper technology in their case. In addition to operating capacity, Frombo et al. (2009a) determined the type and capacity of the conversion technology that would provide the least costly energy. Biomass collection areas can impact the cost of energy considerably. This impact is translated in the transportation cost of biomass. Getting biomass from farther distances would cost more. However, closer supply areas might not be able to provide the energy plant with sufficient biomass. Here, the important decision to answer is how much biomass should be collected from each area. The models in Freppaz et al. (2004), Gunnarsson et al. (2004), Frombo et al. (2009a), Frombo et al. (2009b), and Alam et al. (2010) determined the quantity of biomass that should be transported to the energy plants from potential supply areas.

Deciding about the logistics of forest biomass feedstock is also a significant decision to be made. Where to chip the residues, at source point, at terminal storage, or at the plant? Is it necessary to transport biomass to final destination via storage or direct flow of biomass is possible? Eriksson et al. (1989), Gunnarsson et al. (2004), Kanzian et al. (2009), and Keirstead et al. (2012) planned an optimal supply chain for delivering forest biomass to energy plants.
Chapter 3. Feasibility of using forest biomass for generating heat in a district heating system

3.1 Synopsis

This chapter investigates the feasibility of using local forest biomass for heat generation in a district heating system in Williams Lake, BC. Herein, what determine the feasibility are (1) availability of regional forest biomass, and (2) cost of delivering forest biomass to the gate of heating plant. For assessing the availability of forest biomass, the monthly average heat demand and available biomass are quantified and compared. For estimating the cost of delivered forest biomass, the potential supply chain options and the equipment and machinery required to deliver forest biomass to the heating plant are determined, and then the corresponding costs are calculated. Sensitivity analyses are performed to assess the impact of some important parameters on the total cost of transporting forest biomass to the plant. These parameters include material cost, moisture content, and productive machine hour.

3.2 Heat demand profile of district heating system

Fuel demand of a district heating system depends on three factors: (1) heat demand of buildings, (2) boiler efficiency, and (3) energy content of the fuel. The fuel demand of the district heating system in month t is calculated using Eq. (3-1):

\[
\text{Fuel demand}_t (\text{tonne}) = \frac{\text{Heat demand}_t (\text{GJ})}{\text{Efficiency (\%)} \times \text{Heating value (GJ/tonne-1)}}
\]  

(3-1)

3.2.1 Heat demand of buildings

One method to obtain the space heat demand is energy use intensity method (Ghafghazi 2011). This unit of measurement describes the energy consumption of a building relative to its size. Eq. (3-2) expresses energy use intensity (EUI) over the time period t (EIA 1999):

\[\text{Energy use intensity (EUI)} = \frac{\text{Heat demand}_t (\text{GJ})}{\text{Area (m}^2)} \]  

(3-2)
The HOMER commercial software uses historical energy consumption patterns of similar archetypal buildings in a region to give an estimate of energy use intensity (EUI) (Lambert et al. 2005). Knowing the floor space and monthly energy use intensity of each building type, Eq. (3-3) estimates the monthly average heat demand of a building.

\[ Q_t = \sum_{i=1}^{12} EUI_{i,t} \times A_i \]  

(3-3)

where \( Q_t \) is total heat demand (W) in month \( t \), \( t = 1, 2, 3, \ldots, 12 \), \( EUI_{i,t} \) represents the energy use intensity (W/m\(^2\)) of building type \( i \) in month \( t \), and \( A_i \) is the total heated area (m\(^2\)).

An alternative method to estimate the monthly average space heat demand is to calculate the amount of energy required to maintain the indoor temperature at a certain level usually at human’s comfort level of 18-20 °C (ASHRAE 2009). In this method, the monthly average heat demand is expressed as Eq. (3-4):

\[ Q_t = \sum_{i=1}^{12} U_i A_i (T_{in} - T_{ot}) \]  

(3-4)

where \( Q_t \) is heat demand (W) in month \( t \), \( t = 1, 2, 3, \ldots, 12 \), \( U_i \) is the overall heat transfer coefficient (W/(m\(^2\) °C)) of building type \( i \), \( A_i \) is the total area (m\(^2\)) of building type \( i \), and \( T_{in} \) and \( T_{ot} \) are indoor and outdoor temperatures (°C). This study considers \( T_{in} \) being constant as 18°C. The difference between outdoor temperature and the base temperature of 18 °C is also known as heating degree days. The RETScreen software\(^{12} \) uses the heating degree days to estimate the heat demand of district heating systems (NRCan 2012). The overall heat transfer coefficient \( U \)

\(^{12} \) The RETScreen software is available for download at http://www.retscreen.net/ang/home.php
represents heat losses from different parts of a building such as windows, walls, doors and floors. The value of this coefficient depends on building design and specifications (ASAE 2003).

Each of the two methods discussed here requires information about energy intensity use, area, and the overall heat transfer coefficient of each building type. These data are not available for this case study; thus, these methods cannot be used directly to estimate the heat demand. In this research, the annual energy consumption (Table 1-3) was used to estimate the total annual heat demand, and then assuming that heat demand is proportional to the heating degree days, estimated heat demand was distributed throughout the year using monthly average heating degree days.

The commercial sector in Williams Lake consumes two secondary energy sources: natural gas and hydro (Carson 2012). The secondary energy sources provide energy for space and water heating, space cooling, and operating auxiliary equipment and motors (NRCan 2012). Since the district heating system in this study provides only space heat and hot water to the buildings, the energy consumed for lighting, and operating auxiliary equipment and motors must be subtracted from the total secondary energy use provided in Table 1-3. The average ratios of secondary energy use in BC’s commercial sector by end-use (Table 3-1) obtained from (NRCan 2012a) can be applied to break down the total secondary energy consumption into secondary energy consumption for space heating, heating water, lighting, running equipment and motors in different types of buildings.

<table>
<thead>
<tr>
<th>End use</th>
<th>Services</th>
<th>Offices</th>
<th>Educational</th>
<th>Health care</th>
<th>Recreational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space heating</td>
<td>51.1%</td>
<td>52.1%</td>
<td>50.3%</td>
<td>52.2%</td>
<td></td>
</tr>
<tr>
<td>Water heating</td>
<td>7.7%</td>
<td>7.7%</td>
<td>10.6%</td>
<td>7.7%</td>
<td></td>
</tr>
<tr>
<td>Auxiliary equipment</td>
<td>15.7%</td>
<td>16.0%</td>
<td>15.5%</td>
<td>16.0%</td>
<td></td>
</tr>
<tr>
<td>Auxiliary motors</td>
<td>9.8%</td>
<td>10.0%</td>
<td>9.7%</td>
<td>10.1%</td>
<td></td>
</tr>
<tr>
<td>Lighting</td>
<td>12.1%</td>
<td>12.3%</td>
<td>12.0%</td>
<td>12.3%</td>
<td></td>
</tr>
<tr>
<td>Space cooling</td>
<td>3.5%</td>
<td>1.9%</td>
<td>1.9%</td>
<td>1.7%</td>
<td></td>
</tr>
</tbody>
</table>

Table 3-1: Secondary energy use in commercial sector in BC by end-use—2008
Source: (NRCan 2012a)
After applying the ratios in Table 3-1 to the total secondary use provided in Table 1-3 space heat and hot water demand of the buildings can be estimated (Table 3-2).

<table>
<thead>
<tr>
<th>Building</th>
<th>Space heat (GJ)</th>
<th>Hot water (GJ)</th>
<th>Total heat demand (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCMP Detachment</td>
<td>524</td>
<td>79</td>
<td>603</td>
</tr>
<tr>
<td>Williams Lake Senior Secondary School</td>
<td>7,607</td>
<td>1,124</td>
<td>8,731</td>
</tr>
<tr>
<td>Cariboo Memorial Hospital</td>
<td>19,723</td>
<td>4,156</td>
<td>23,879</td>
</tr>
<tr>
<td>Cariboo Memorial Complex-Pool</td>
<td>4,290</td>
<td>633</td>
<td>4,923</td>
</tr>
<tr>
<td>Cariboo Memorial Complex-Arena</td>
<td>5,779</td>
<td>445</td>
<td>6,224</td>
</tr>
<tr>
<td>Total</td>
<td>37,922</td>
<td>6,437</td>
<td>44,359</td>
</tr>
<tr>
<td>Monthly average</td>
<td>3,160</td>
<td>536</td>
<td>3,697</td>
</tr>
</tbody>
</table>

The district heating system must provide 44,359 GJ or 12,322 MWh\(^{13}\) of thermal energy to its customers. Assuming that this heating plant operates 8760 hours per year (24 hours a day, 365 days a year), the district heating system has to generate 1.4 MW of thermal energy.

The heat demand is not constant throughout the year, reaches its maximum in the winter and its minimum in the summer time. Although hot water demand may be 30% to 50% higher in the winter compared to that in the summer (NRCan 2012b), this study assumes that hot water demand is steadfast over the course of the year and equals monthly average hot water consumption of 536 GJ or 149 MWh (Table 3-2). In the RETScreen software, a constant hot water demand is considered and it is calculated as a fraction of the annual heat demand (NRCan 2012b). Similarly, monthly hot water demand was constant in Ghafghazi (2011).

\(^{13}\)1 GJ = 0.27778 MWh
The annual space heat demand calculated in Table 3-2 is distributed over the course of the year using Eq. (3-5) and the total monthly average space heat demand is defined in Eq. (3-6).

\[
\text{HD}_{it} \% = \frac{Q_{it}}{Q_{\text{annual-i}}} = \frac{U_i A_i (18-T_{ot})}{\sum_{t=1}^{12} U_i A_i (18-T_{ot})} = \frac{U_i A_i (18-T_{ot})}{U_i A_i \sum_{t=1}^{12} (18-T_{ot})} = \frac{\sum_{t=1}^{12} (18-T_{ot})}{\sum_{t=1}^{12} (18-T_{ot})} \tag{3-5}
\]

\[
Q_t = \sum_t Q_{it} \tag{3-6}
\]

where \( Q_{it} \) and \( Q_{\text{annual-i}} \) are the space heat demand (W) in month \( t \), \( t = 1,2,3,\ldots,12 \) and the annual space heat demand (W) of building I, \( U_i \), and \( A_i \) are the overall heat transfer coefficient (W/(m\(^2\) °C)), and total heating area (m\(^2\)) of building i, respectively. \( T_{ot} \) (°C) is the average outdoor temperature of month \( t \).
Table 3-3 compiles the monthly average heating degree days (HDD) in Williams Lake, BC obtained from Environment Canada (2012b). Table 3-4 and Figure 3.1 present the monthly average thermal energy demand of the buildings calculated through Eq. (3-6).

Table 3-3: Monthly average heating degree days

Source: Environment Canada (2012b)

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating degree days % of total</td>
<td>807</td>
<td>637</td>
<td>592</td>
<td>482</td>
<td>237</td>
<td>173</td>
<td>88</td>
<td>114</td>
<td>226</td>
<td>403</td>
<td>511</td>
<td>942</td>
<td>5216</td>
</tr>
<tr>
<td></td>
<td>15.5</td>
<td>12.2</td>
<td>11.4</td>
<td>9.2</td>
<td>4.6</td>
<td>3.3</td>
<td>1.7</td>
<td>2.2</td>
<td>4.3</td>
<td>7.7</td>
<td>9.8</td>
<td>18.1</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Table 3-4: Monthly average heat demand of the district heating system

<table>
<thead>
<tr>
<th>Month</th>
<th>Space Heat Demand (GJ)</th>
<th>Hot water Demand (GJ)</th>
<th>Heat demand (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>5,869</td>
<td>536</td>
<td>6,406</td>
</tr>
<tr>
<td>Feb</td>
<td>4,632</td>
<td>536</td>
<td>5,168</td>
</tr>
<tr>
<td>Mar</td>
<td>4,305</td>
<td>536</td>
<td>4,842</td>
</tr>
<tr>
<td>Apr</td>
<td>3,505</td>
<td>536</td>
<td>4,041</td>
</tr>
<tr>
<td>May</td>
<td>1,726</td>
<td>536</td>
<td>2,262</td>
</tr>
<tr>
<td>Jun</td>
<td>1,262</td>
<td>536</td>
<td>1,799</td>
</tr>
<tr>
<td>Jul</td>
<td>643</td>
<td>536</td>
<td>1,179</td>
</tr>
<tr>
<td>Aug</td>
<td>832</td>
<td>536</td>
<td>1,369</td>
</tr>
<tr>
<td>Sep</td>
<td>1,648</td>
<td>536</td>
<td>2,185</td>
</tr>
<tr>
<td>Oct</td>
<td>2,932</td>
<td>536</td>
<td>3,469</td>
</tr>
<tr>
<td>Nov</td>
<td>3,716</td>
<td>536</td>
<td>4,252</td>
</tr>
<tr>
<td>Dec</td>
<td>6,851</td>
<td>536</td>
<td>7,387</td>
</tr>
</tbody>
</table>
Figure 3.1: Monthly average heat demand of the district heating system
3.2.2 Boiler efficiency

Boiler efficiency depends on the fuel moisture content. It varies from 84% to 49% in systems using biomass fuel with moisture content of 0% to 60% (Prasad 1995). Combustion of high moisture content material is less efficient than combustion of dryer material because evaporating the moisture within the feedstock requires extra heat (Prasad 1995). Herein, the boiler efficiency of 66% for wood residues was assumed based on Chau et al. (2009).

3.2.3 Energy content

Energy content of biomass is the amount of energy that can be generated from a unit mass of biomass. As it was stated previously in the case study section, energy content of logging residues and sawmill wastes average about 19.5 GJ.tonne\(^{-1}\) and 18.3 GJ.tonne\(^{-1}\), respectively.

Table 3-5 calculates the annual fuel demand of each individual biomass source assuming that the district heating system is operating only on one fuel type.

<table>
<thead>
<tr>
<th>Description</th>
<th>Sawmill residues</th>
<th>Gavin Lake residues</th>
<th>Knife Creek residues</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content (% wb)</td>
<td>30.52 (^{a})</td>
<td>29.6 (^{b})</td>
<td>29.6 (^{b})</td>
<td>30</td>
</tr>
<tr>
<td>Heating value (GJ.Odt(^{-1}))</td>
<td>18.3(^{a})</td>
<td>19.5 (^{b})</td>
<td>19.5 (^{b})</td>
<td>18.81</td>
</tr>
<tr>
<td>Boiler efficiency (^{c}) (%)</td>
<td>66</td>
<td>66</td>
<td>66</td>
<td>66</td>
</tr>
<tr>
<td>Annual fuel demand (Odt)</td>
<td>3707</td>
<td>3446</td>
<td>3446</td>
<td>3572</td>
</tr>
</tbody>
</table>

(Annual fuel demand shows the demand of the DHS if it is running only on one fuel type)

\(^{a}\) derived from Kehbila (2010)

\(^{b}\) average from case 3 in Jafari Naimi et al. (2009)

\(^{c}\) Chau et al. (2009)
3.3 Biomass availability

3.3.1 Estimating quantity of sawmill residues

No data is available on the waste production in sawmills listed in Table 1-5. One way to estimate the biomass production of these sawmills is to obtain the monthly volume scaled at each of sawmills; then, to use recovery factors to break down sawlog into sawn timber, wood chips, sawdust, shavings, trim ends, and bark. Table 3-6 compiles the estimates of product recovery from lumber mills in British Columbia. Recovery factors define the amount of products produced from 1 m³ of input logs.

Table 3-6: Estimates of product recovery from lumber mills in British Columbia

<table>
<thead>
<tr>
<th>Product Recovery Factor</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumber recovery factor</td>
<td>Mfbm. m³¹⁴</td>
<td>0.278</td>
</tr>
<tr>
<td>Chips recovery factor</td>
<td>Odt. Mfbm⁻¹</td>
<td>0.38</td>
</tr>
<tr>
<td>Sawdust recovery factor</td>
<td>Odt. Mfbm⁻¹</td>
<td>0.06</td>
</tr>
<tr>
<td>Shavings recovery factor</td>
<td>Odt. Mfbm⁻¹</td>
<td>0.06</td>
</tr>
<tr>
<td>Trim ends recovery factor</td>
<td>Odt. Mfbm⁻¹</td>
<td>0.02</td>
</tr>
<tr>
<td>Bark recovery factor</td>
<td>Odt. Mfbm⁻¹</td>
<td>0.16</td>
</tr>
</tbody>
</table>

¹⁴ MOF (2011b)

Kehbila (2010)

Monthly volume (m³) of sawlogs scaled at each mill location is obtained from the British Columbia’s scale data management and invoicing system, Harvest Billing System (HBS)¹⁵, for the 5-year period of 2007-2011. For the purpose of this study, it is assumed that sawmills do not build up inventories and they process all the sawlogs they receive each month within that month. The records from Harvest Billing System indicate that many of the identified sawmills have not received wood frequently. Therefore, they cannot be considered as reliable suppliers. Only sawmills that had been operating for 5 consecutive years from 2007 to 2011 are considered for

¹⁴ 1000 board feet, volume of a board 1 foot long, 1 foot wide, and 1 inch thick

¹⁵ https://www15.for.gov.bc.ca/hbs/
further analysis. Table 3-7 summarizes the monthly quantity of biomass available at each of those sawmills (average of 5 years from 2007 to 2011).

Table 3-7: Monthly residue production (Odt) by sawmill- Average of 5 years (2007-2011)

<table>
<thead>
<tr>
<th>Scale Site</th>
<th>Total by-products (Odt)- Average (2007-2011)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Jan</td>
</tr>
<tr>
<td>62A</td>
<td>13</td>
</tr>
<tr>
<td>62C</td>
<td>79</td>
</tr>
<tr>
<td>62F</td>
<td>167</td>
</tr>
<tr>
<td>62V</td>
<td>20</td>
</tr>
<tr>
<td>6FD</td>
<td>20</td>
</tr>
<tr>
<td>6L2</td>
<td>10</td>
</tr>
<tr>
<td>6T2</td>
<td>39</td>
</tr>
<tr>
<td>C80</td>
<td>18</td>
</tr>
<tr>
<td>C85</td>
<td>76</td>
</tr>
<tr>
<td>Total</td>
<td>441</td>
</tr>
</tbody>
</table>

Local sawmills can provide an annual average of 2,495 Odt of residues to the district heating system annually. Figure 3.2 shows the composition of different by-products in sawmill wastes.

Figure 3.2: Sawmill residues by their by-products
3.3.2 Estimating quantity of logging residues

British Columbia uses “full tree to roadside” harvest method (Bradley 2007), in which felled trees are forwarded to roadside with tops and branches, and then they are processed at roadside. With this method, wastes are left in piles at roadside. To estimate the quantity of logging residues in British Columbia, Bradley (2007) considered that 25% of harvested round wood (m³) is turned into waste (m³). Then, the conversion factor of 0.4 Odt.m⁻³ converted cubic meter of wood wastes to Odt of wood wastes. Afterward, 80% of estimated quantity of wastes was considered as roadside slash and the rest 20% was considered as stump. This research applies the same percentages to estimate the quantity of roadside residues, while a conversion factor of 0.48 Odt.m⁻³ is used to convert m³ to Odt. This conversion factor is the average from seven area projects in Williams Lake (Skea et al. 2009).

In addition to residue percentage, the annual harvesting history in Gavin Lake and Knife Creek blocks is required which is provided by Alex Fraser Research Forest.

Table 3-8 estimates the monthly average of logging residues in these blocks over the 5 year period of 2007-2011. Figure 3.3 shows the distribution of logging residue availability over the year.

---

16 The percentages used to estimate the quantity of logging residues in the present work are comparable with the ratio of residue produced to volume scaled in the case study 2 (Tolko Cutting Permits) in Skea et al. (2009)
Table 3-8: Monthly average of roadside residue production in Gavin Lake and Knife Creek blocks of UBC AFRF

<table>
<thead>
<tr>
<th>Month</th>
<th>Gavin Lake</th>
<th>Knife Creek</th>
<th>Gavin Lake</th>
<th>Knife Creek</th>
<th>Gavin Lake</th>
<th>Knife Creek</th>
<th>Gavin Lake</th>
<th>Knife Creek</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average roundwood harvest (m³)</td>
<td>Residue production (m³)</td>
<td>Residue production (Odt)</td>
<td>Roadside residue production (Odt)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>25% of harvest</td>
<td>0.48 Odt per m³</td>
<td>80% of residue production</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jan</td>
<td>3,824</td>
<td>956</td>
<td>459</td>
<td>367</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1,428</td>
<td>357</td>
<td>171</td>
<td>137</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feb</td>
<td>3,376</td>
<td>844</td>
<td>405</td>
<td>324</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2,095</td>
<td>524</td>
<td>251</td>
<td>201</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mar</td>
<td>649</td>
<td>162</td>
<td>78</td>
<td>62</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Apr</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>3</td>
<td>1</td>
<td>-</td>
<td>-</td>
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<td></td>
<td></td>
<td></td>
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<td>-</td>
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<td></td>
</tr>
<tr>
<td>Jun</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jul</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aug</td>
<td>1,214</td>
<td>303</td>
<td>146</td>
<td>117</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sep</td>
<td>1,892</td>
<td>473</td>
<td>227</td>
<td>182</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct</td>
<td>1,587</td>
<td>397</td>
<td>190</td>
<td>152</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nov</td>
<td>1,666</td>
<td>416</td>
<td>200</td>
<td>160</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dec</td>
<td>1,671</td>
<td>418</td>
<td>200</td>
<td>160</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>10,883</td>
<td>2,721</td>
<td>1,306</td>
<td>1,306</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.3: Estimated monthly quantity of logging residues at Gavin Lake and Knife Creek blocks of UBC AFRF
3.4 Comparing annual supply and demand

A total average of 4552 Odt of residues is available annually. Sawmill residues account for 55% of total biomass available, logging residues at Gavin Lake and Knife Creek account for 33% and 12% of total local forest biomass, respectively. Considering a weighted average energy content of 18.77 GJ.Odt$^{-1}$, this quantity of biomass can generate 85,446 GJ of energy. At the conversion efficiency of 66%, the district heating system requires 67,211 GJ of forest fuel to fulfill the thermal energy demand of its customers. Thus, the annual supply exceeds the annual demand. However, availability of biomass fluctuates in a year and in some months there may not be enough biomass to meet the demand.

Figure 3.4 plots the monthly fuel demand of the district heating system and availability of different types of forest residues in Gigajoules. Measuring the demand and supply quantities in Gigajoules offsets the effect of heating value in the fuel demand and a reasonable comparison can be made between supply and demand quantities. The overall quantity of fuel demand in month $t$, and the amount of biomass type $i$ in month $t$ can be calculated using Eq. (3-7) and Eq. (3-8), respectively.

\[
\text{Fuel demand}_t (\text{GJ}) = \frac{\text{Heat demand}_t (\text{GJ})}{\text{Efficiency} \, (\%)}
\]  

\[
\text{Biomass supply}_i (\text{GJ}) = \text{Biomass quantity}_i (\text{tonnes}) \times \text{Heating value}_i (\text{GJ. tonne}^{-1})
\]  

Figure 3.4 illustrates that a considerable gap exists between supply and demand in April, May, June, July, and December; however, storing the surplus residues in the other months buffers this gap since the annual supply is 18,138 GJ higher than annual demand.
In addition to the availability of biomass, the cost of delivering forest biomass to the gate of plant is another determining factor in the feasibility study. Forest biomass delivery cost should be comparable with alternative sources of energy particularly conventional energy sources, natural gas in this study. Biomass can be transported to the heating plant using different supply chains. In this section, the supply chain options to deliver biomass from source points to the plant are determined, the logistical solutions are defined, and the costs associated with each option are calculated and presented.
3.5.1 Supply chain options

Several activities are involved in supplying biomass from source points to energy plants. The most common activities in forest residue supply chain are biomass collection, comminution, and off-road and highway transportation. Depending on the biomass type, conversion technology and region, storage and drying may also take place in the supply chain. In some seasons, the available biomass may not be enough to fulfill the heat demand since the quantity of biomass fluctuates seasonally. For this situation direct delivery of biomass to the plant is not possible and the extra biomass in other months should be accumulated in the terminal storage to balance the gap between supply and demand. In addition to ensuring a secure fuel supply, the storage process may reduce the moisture content of biomass and improve the fuel quality (Kanzian et al. 2009).

Logging residues and sawmill residues can be transported to the plant either directly or indirectly via storage. When biomass transportation is via storage, the design of supply chain varies depending on the location of the chipping process. Biomass might be chipped at source locations, roadside for logging residues or at sawmills for sawmill residues, or at the terminal storage. Another option is to chip at plant location. However, because of dust and noise produced during the chipping process this option is not allowable for this case study in which the heating plant is located close to the residential area. Figure 3.5 shows the supply chain designs considered in this research.

![Figure 3.5: Potential supply chain options](image-url)
3.5.2 Logistical solutions, equipment and machines

- Pre-processing

Before it can be used by an energy conversion process, forest residue has to be chipped or ground into smaller size (Dempster et al. 2008). Chipping or grinding forest residue makes its handling easier and increases its bulk density (Dempster et al. 2008). Chippers and grinders can be used to comminute forest residues. Two different categories of chippers are available, disc and drum chippers. Disc chippers are often used to chip whole trees, while drum chippers are best suited for chipping logging residues. Drum chippers produce more even sized woodchips than disc chippers and they are not as sensitive to impurities as disc chippers. Grinders are also used for chipping logging residues. Although grinders are much more indulgent to impurities such as rock and metal, they produce uneven sized woodchips with large splinters that increases the risk of damage to the fuel conveyor in small sized plants (Alakangas et al. 1999).

In the present work, the Dynamic Cone-Head mobile chipper model 535 (Figure 3.6) with the engine output of 275 HP (205 KW) is examined. This chipper is considered because of its small size and mobility, since the piles of residues are very small in size and distributed over a large area. The chipper weighs 7,870 kg, is 7.62 m long, 2.29 m wide and 3.58 m high and has an output chip capacity of 38 GMT.PMH⁻¹ (Dynamic Manufacturing). The John Deere 225 D excavator with the engine output of 159 HP (118 KW) (John Deere 2012) feeds the material into the chipper. The 23 cm long × 183 cm wide infeed bed takes the material toward the chipping drum using a conveyer chain powered with hydraulic motors. Two horizontal feed wheels with the opening throat of 53 cm high × 71 cm width and with sharp carbon steel blades pull the material to the chipping drum. The produced chips are directly discharged to the chip van through the chip tube (Dynamic Manufacturing).
- **Storage**

Many storage facilities are now built using fabric on frame technologies. The local pellet plant, Pinnacle Renewable Energy Group, uses this technology to store ground wood. In this study, a coverall structure of T-series of Norseman Structure (Figure 3.7) is taken into account for woodchips while non-chipped residues are stored in an open area. This structure is recommended by Skea (Personal communication on Mar 1-2012) and consists of a galvanized steel framework roofed with high density polyethylene fabric coated with 4 mil coat to prevent ultraviolet damage. Fabric on frame structures can be constructed on concrete block (wall mount), or on concrete slab, asphalt pad, or directly on the ground without any foundation (ground mount) (Norseman Structures).

![Figure 3.6: Dynamic Cone Head mobile chipper model 535](image1)

![Figure 3.7: Fabric on frame storage for storing woodchips](image2)

---

17 The images are provided by Kazu Miyoshi, the International Sales Manager at Dynamic Manufacturing LCC and the permission to use these images is available.
Transportation

Local biomass might be transported using several different methods including trucking, rail transportation, inland waterway transportation, and shipping. Trucking is the most common transportation method. Dump trucks are widely used for hauling non-chipped residues. Walking floor trailers are best suited for transportation of wood chips in bulk. The set of a highway tractor and a 16.2 m (53’) tri-axle walking floor trailer (Figure 3.8-a) with the box capacity of 113 m$^3$ transports woodchips and sawmill residues from the source points or the terminal storage to the heating plant. A tri-axle dump truck (Figure 3.8-b) with the box capacity of 67 m$^3$ is in charge of transporting loose debris (non-chipped residues) from resources to the storage. Table 3-9 includes the transportation vehicles and their specifications.

Figure 3.8: (a) 53’ semi-trailer chip van (110 m$^3$), (b) 3 axle truck (42 m$^3$)\(^{19}\)

\(^{18}\) The image is provided by Brian Sweet, the Interior Sales Manager at Span Master Structures LTD. and the permission to use this image is available.

\(^{19}\) The images are provided by Don Skea, the Operations Supervisor at UBC Alex Fraser Research forest and the permission to use these images is available.
Table 3.9: Haulage vehicle characteristics

<table>
<thead>
<tr>
<th>Hauling equipment</th>
<th>Volume capacity (m$^3$)</th>
<th>Rate$^{20}$ $$/h$^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>53’ high chip van</td>
<td>113$^a$</td>
<td>124.28$^b$</td>
</tr>
<tr>
<td>3 axle truck</td>
<td>67$^a$</td>
<td>103$^b$</td>
</tr>
</tbody>
</table>

$^a$ MacDonald (2011)

$^b$ Skea (Personal communication on Mar 1-2012)

3.5.3 Cost estimation

The total delivery cost of forest biomass to the gate of the plant can be divided into machinery (loader and chipper) costs, storage cost, and transportation cost. Machinery costs include capital and operating costs of loader and chipper. Storage cost is mainly the investment cost of the storage. In-storage handling cost is calculated separately as pre-processing costs. Transportation cost is the cost incurred while moving forest biomass to the heating plant. In this study, the loader and the chipper are assumed to be owned while, transportation vehicles are rented.

- Machinery cost

Cost of machines consists of (1) fixed costs: annualized capital cost including depreciation of machines and insurance cost, and (2) variable costs including fuel, oil and lubricant, labour, and repair and maintenance costs. Table 3-10 shows the input data used to calculate the cost of machines. In Table 3-10, scheduled machine hours (SMH) and productive machine hours (PMH) are calculated using Eq. (3-9) and Eq. (3-10), respectively.

\[
SMH = \text{Working hours per day} \times \text{Working days per year} \tag{3-9}
\]

\[
PMH = SMH \times \text{Utilization} \tag{3-10}
\]

In the same table, the annual depreciation of the machines is calculated based on straight line method using Eq. (3-11) (Fraser et al. 2000):

---

$^{20}$ The original rates were 2008’s. An average inflation rate of 1.96% was adopted from BOC (2012).
\[ D_{sl} = \frac{P - S}{n} \]  

where \( D_{sl} \) is the annual depreciation amount, \( P \) is the purchase price, \( S \) is the salvage value, and \( n \) is the economic life of the machines.

Table 3-10: Input data for loading and chipping cost calculations

<table>
<thead>
<tr>
<th>Data</th>
<th>Loader</th>
<th>Chipper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchase price ($)</td>
<td>240,000(^a)</td>
<td>200,000(^b)</td>
</tr>
<tr>
<td>Machine life (yr)</td>
<td>5(^c)</td>
<td>5(^c)</td>
</tr>
<tr>
<td>Salvage value, % of purchase price</td>
<td>30(^c)</td>
<td>20(^c)</td>
</tr>
<tr>
<td>Utilization rate (%)</td>
<td>65(^c)</td>
<td>75(^c)</td>
</tr>
<tr>
<td>Repair and maintenance, % of depreciation</td>
<td>90(^c)</td>
<td>100(^c)</td>
</tr>
<tr>
<td>Interest rate (%)</td>
<td>6.5(^d)</td>
<td>6.5(^d)</td>
</tr>
<tr>
<td>Insurance and tax rate, % of purchase price</td>
<td>2.50(^c)</td>
<td>2.50(^d)</td>
</tr>
<tr>
<td>Fuel (diesel) consumption (L.PMH(^{-1}))</td>
<td>13(^c)</td>
<td>27(^b)</td>
</tr>
<tr>
<td>Fuel cost ($L(^{-1}))</td>
<td>1.30(^d)</td>
<td>1.30(^d)</td>
</tr>
<tr>
<td>Lubrication cost (%), percent of fuel cost</td>
<td>36.8(^d)</td>
<td>36.8(^d)</td>
</tr>
<tr>
<td>Number of operators</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Operator wage ($hr(^{-1}))</td>
<td>25(^d)</td>
<td>25(^d)</td>
</tr>
<tr>
<td>Operator benefits (%), percent of wage</td>
<td>30(^d)</td>
<td>30(^d)</td>
</tr>
<tr>
<td>Productivity (GMT.PMH(^{-1}))</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Working hours per day</td>
<td>9(^d)</td>
<td>9(^d)</td>
</tr>
<tr>
<td>Working days per year</td>
<td>133(^d)</td>
<td>133(^d)</td>
</tr>
<tr>
<td>Scheduled machine hours per year (SMH.yr(^{-1}))</td>
<td>1,200</td>
<td>1,200</td>
</tr>
<tr>
<td>Productive machine hours per year (PMH.yr(^{-1}))</td>
<td>780</td>
<td>900</td>
</tr>
<tr>
<td>Salvage value ($)</td>
<td>102,600</td>
<td>40,000</td>
</tr>
<tr>
<td>Annual depreciation ($)</td>
<td>47,880</td>
<td>32,000</td>
</tr>
</tbody>
</table>

\(^a\) Construction Equipment Guide
\(^b\) Miyoshi (Personal communication on Feb 28-2012)
\(^c\) Brinker et al. (2002)
\(^d\) Skea (Personal communication on Mar 1-2012)
\(^e\) Vancouver Gas Prices
The output capacity of the chipper is 38 GMT.PMH\(^1\) (Dynamic Manufacturing). The machine productivity is very case dependent and depends on several factors such as tree species, residue size, soil condition, and ground slope. Equipment productivity is measured using time studies in the field. Since field study was not possible, the chipper productivity is considered to be 50\% of its output capacity (adopted from Skea et al. (2009). It is assumed that the loader does not restrict the chipper and the same productivity is taken into account for the loader.

Total cost of machines \((C_{tot})\) is expressed as Eq. (3-12):

\[
\text{Total cost of machine per year} (C_{tot}) = \text{Fixed cost} (C_0) + \text{Insurance cost} (C_i) + \text{Fuel and oil costs} (C_f) + \text{Labor cost} (C_l) + \text{Repair cost} (C_r)
\]

(3-12)

and:

\[
C_0 = \frac{P \times i(1+i)^n}{(1+i)^n-1} \times \frac{SV \times i}{(1+i)^n-1}
\]

(3-13)

where \(C_0\) is the annual machine fixed costs, \(P\) is the purchase price of the machine, \(SV\) is the salvage value of the machine at the end of the expected service life of the machine, \(n\), and \(i\) is the interest rate.

\[
C_i = P \times i_c
\]

(3-14)

\(C_i\) is the annual insurance cost, and \(i_c\) is the percentage of purchase price used to calculate the insurance cost.

\[
C_f = F \times F_c \times (1+i_o) \times PMH
\]

(3-15)

where \(C_f\) is the fuel and oil costs, \(F\) is the fuel consumption in l.PMH\(^1\), \(F_c\) is the fuel cost in $.l\(^1\), and \(i_o\) is the percentage of fuel cost used for oil and lubricant cost calculation.

\[
C_l = N \times w \times (1+i) \times SMH
\]

(3-16)
where $C_l$ is the labour cost, $N$ is the number of operators, $w$ is the operator wage in $.SMH^{-1}$, $i_l$ is the percentage of the operator wage to calculate the labour benefits.

\[
C_r = \frac{P(1-i_{sv})}{n} \times i_r
\]  

(3-17)

where $C_r$ is the annual repair cost, $P$ is the purchase price of machine, $i_{sv}$ is the percentage of purchase price that gives the salvage value, $i_r$ is the percentage of salvage value used to calculate repair and maintenance cost, and $n$ is the economic life of machine.

Once the annual total machines cost ($C_{tot}$) has been calculated, the cost per unit of biomass processed can be obtained using Eq. (3-18):

\[
\text{per unit cost} = \frac{C_{tot}}{\text{Annual biomass production}}
\]  

(3-18)

and annual biomass production is calculated using Eq. (3-19):

\[
\text{Annual biomass production} = \text{PMH} \times \text{Machine productivity}
\]  

(3-19)

The costs are always converted from $.GMT^{-1}$ to $.Odt^{-1}$ using Eq. (3-20):

\[
$. Odt^{-1} = \frac{$.GMT}{1 - MC\%}
\]  

(3-20)

where $MC\%$ is the moisture content of the biomass.
Table 3-11 summarizes the cost of machines.

Table 3-11: Machines and equipment cost

<table>
<thead>
<tr>
<th></th>
<th>Loader</th>
<th>Chipper</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fixed Costs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital ($/yr⁻¹)</td>
<td>$45,106.60</td>
<td>$41,101.53</td>
</tr>
<tr>
<td>Insurance ($/yr⁻¹)</td>
<td>$6,000.00</td>
<td>$5,000.00</td>
</tr>
<tr>
<td><strong>Variable costs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel and oil ($/yr⁻¹)</td>
<td>$18,033.60</td>
<td>$43,218.00</td>
</tr>
<tr>
<td>Repair and maintenance ($/yr⁻¹)</td>
<td>$30,240.00</td>
<td>$32,000.00</td>
</tr>
<tr>
<td>Labour cost ($/yr⁻¹)</td>
<td>$39,000.00</td>
<td>$0.00</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td>$138,379.88</td>
<td>$121,316.65</td>
</tr>
<tr>
<td>Annual biomass production (GMTy⁻¹)</td>
<td>14,820</td>
<td>17,100</td>
</tr>
<tr>
<td>Per unit cost ($/GMT⁻¹)</td>
<td>9.34</td>
<td>7.09</td>
</tr>
<tr>
<td>Per unit cost ($/Odt⁻¹) - sawmill residues (MC: 30.52% wb)</td>
<td>13.44</td>
<td>10.21</td>
</tr>
<tr>
<td>Per unit cost ($/Odt⁻¹) - logging residues (MC: 29.58% wb)</td>
<td>13.26</td>
<td>10.07</td>
</tr>
</tbody>
</table>

- Storage cost

Calculating storage cost requires the storage capacity as an input to estimate the investment cost. The method used by Gronalt et al. (2007) is adopted here to calculate the storage capacity. Gronalt et al. (2007) applied an iterative process to estimate the monthly inventory of the storage over the course of the year. The capacity of the storage was considered as the maximum monthly stock at the terminal. In Gronalt et al. (2007), the entire available biomass in the region was utilized as fuel in a number of district heating systems.

In the present work, the storage capacity is estimated such that the fuel demand of each month is fulfilled through the terminal storage, and the terminal storage always keeps a certain level of stock known as safety stock. In the months with higher demand than supply, the gap between supply and demand is transported to the storage in the months with extra biomass. Since there is no access to forest areas from March 15th to June 15th, meeting the heat demand in this time period is challenging. To ensure that no biomass shortage occurs in these months, the terminal storage should always keep a minimum of 325 Odt, the maximum heat demand in this time
period. However, this level of safety stock is more than enough for the summer time. The safety stock for the months July, August, and September is considered as 100 Odt.

Knowing the storage capacity, the storage cost is calculated in Table 3-13 using Eq. (3-21):

\[
C_s = \text{Total investment cost (\$)} \times \frac{i(1+i)^n}{(1+i)^n - 1}
\]

(3-21)

where \( C_s \) is the annualized investment cost of the storage, \( i \) is the interest rate, and \( n \) is the economic life of the storage.

The storage should accommodate 744 Odt of biomass. Considering that each 1000 m\(^3\) loose biomass requires 200 m\(^2\) of area (Kanzian et al. 2009) and 1m\(^3\) loose of wood corresponds to 0.18 Odt of wood (Skea et al. 2009), the area of storage will be 827 m\(^2\).

Table 3-12: Estimating storage capacity

<table>
<thead>
<tr>
<th>Month</th>
<th>Accessible Supply (Odt)</th>
<th>Extra biomass (Odt)</th>
<th>Supply to Terminal (Odt)</th>
<th>Fuel Demand (Odt)</th>
<th>Terminal Stock (Odt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>945</td>
<td>104</td>
<td>841</td>
<td>516</td>
<td>325</td>
</tr>
<tr>
<td>February</td>
<td>854</td>
<td>52</td>
<td>802</td>
<td>416</td>
<td>711</td>
</tr>
<tr>
<td>March</td>
<td>423</td>
<td>-</td>
<td>423</td>
<td>390</td>
<td>744</td>
</tr>
<tr>
<td>April</td>
<td>145</td>
<td>-</td>
<td>145</td>
<td>325</td>
<td>564</td>
</tr>
<tr>
<td>May</td>
<td>41</td>
<td>-</td>
<td>41</td>
<td>182</td>
<td>422</td>
</tr>
<tr>
<td>June</td>
<td>47</td>
<td>-</td>
<td>47</td>
<td>145</td>
<td>325</td>
</tr>
<tr>
<td>July</td>
<td>55</td>
<td>-</td>
<td>55</td>
<td>95</td>
<td>285</td>
</tr>
<tr>
<td>August</td>
<td>223</td>
<td>113</td>
<td>110</td>
<td>110</td>
<td>285</td>
</tr>
<tr>
<td>September</td>
<td>395</td>
<td>219</td>
<td>176</td>
<td>176</td>
<td>285</td>
</tr>
<tr>
<td>October</td>
<td>350</td>
<td>29</td>
<td>321</td>
<td>279</td>
<td>325</td>
</tr>
<tr>
<td>November</td>
<td>546</td>
<td>105</td>
<td>441</td>
<td>342</td>
<td>424</td>
</tr>
<tr>
<td>December</td>
<td>496</td>
<td>-</td>
<td>496</td>
<td>595</td>
<td>325</td>
</tr>
</tbody>
</table>

Capacity 744
Table 3-13: Storage metrics

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment cost ($. m(^{-2}))</td>
<td>194(^a)</td>
</tr>
<tr>
<td>Annual O&amp;M cost (% of investment cost)</td>
<td>0</td>
</tr>
<tr>
<td>Life (years)</td>
<td>20</td>
</tr>
<tr>
<td>Interest rate</td>
<td>6.5%</td>
</tr>
<tr>
<td>Estimated area (m(^2))</td>
<td>827</td>
</tr>
<tr>
<td>Annual storage Cost</td>
<td>14,594</td>
</tr>
<tr>
<td>Total annual inventory (Odt)</td>
<td>5,017(^b)</td>
</tr>
<tr>
<td>Storage cost ($.Odt(^{-1}))</td>
<td>2.90</td>
</tr>
</tbody>
</table>

Source: \(^a\) Sweet (Personal communication on Apr 27-2012)

\(^b\) This quantity is the total of monthly terminal stocks over the year.

- Transportation Cost

Transportation cost varies depending on the supply chain design. When forest fuel is transported to the heating plant directly, transportation is achieved in one step from the source to the plant, while when there is storage in the supply chain, transportation of woody biomass takes place in two steps: (1) transporting from the source to the storage and (2) from the storage to the plant. Assuming the driving time empty is equivalent to the driving time loaded, transportation cost is expressed using Eq. (3-22) (Gautam et al. 2010):

\[
C_t = \frac{R \times (2 \times T_d + T_w)}{W}
\]  

(3-22)

\(C_t\) is the transportation cost in $./GMT\(^{-1}\), \(R\) is the hourly rate of transportation in $./hr\(^{-1}\), \(T_d\) is transportation time in hours (hrs.), \(T_w\) is the waiting time for loading, unloading, and other unavoidable delays (hrs.), and \(W\) is the load weight (GMT) and calculated taking into account the bulk density of the residues (GMT.m\(^{-3}\)) and the capacity of the transportation vehicle (m\(^3\)) using Eq. (3-23):

\[
W = \text{Bulk density (tonne.m}^3\text{)} \times \text{Vehicle capacity (m}^3\text{)}
\]  

(3-23)
As Eq. (3-23) shows, to calculate the transportation cost, it is assumed that trucks are volume limited. One important consideration is the payload that a truck is allowed to carry. For the residues with moisture content below 38%, MacDonald (2011) suggested the payload of 17.7 Odt for 53’ high chip van (113 m³) and 10.5 Odt for 3 axle truck (67 m³). For the residues with higher moisture content, the trucks are weight limited and the above-mentioned payload cannot be used anymore. Table 3-14 shows the load weights used to calculate the transportation cost.

Table 3-14: Load weights for calculating transportation cost

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Load</th>
<th>Bulk density (tonne.m⁻³)</th>
<th>Load weight (Odt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>53’ high chip van</td>
<td>Chipped sawmill residues</td>
<td>0.21541⁵</td>
<td>16.90</td>
</tr>
<tr>
<td>53’ high chip van</td>
<td>Chipped logging residues</td>
<td>0.21541⁵</td>
<td>17.14</td>
</tr>
<tr>
<td>3 axle truck</td>
<td>Non-chipped logging residues</td>
<td>0.11838 b</td>
<td>7.93</td>
</tr>
</tbody>
</table>

⁵ obtained from case 3 of Jafari Naimi et al. (2009)
b averages from 7 case studies in Skea et al. (2009)

Figure 3.9 illustrates the transportation cost for direct flow and flow via storage of sawmill residues to the heating plant and explains the relationship between transportation cost and distance from the catchment areas to the district heating system.

In the direct flow of sawmill residues to the plant, the transportation cost of forest biomass might be as low as $8.57 Odt⁻¹ when the biomass is obtained from 6.8 km (5 minutes) of the plant and it can be as high as $33.31 Odt⁻¹ when the biomass is transported from 88.2 km (106 minutes) from the heating plant. The average direct transportation cost of sawmill residues to the plant is $19.76 Odt⁻¹. When the biomass delivery is via terminal storage, the transportation of sawmill residues varies from $19.11 Odt⁻¹ to $44.09 Odt⁻¹ depending on the distance from the heating plant. The average transportation cost in this supply chain option is $30.40 Odt⁻¹ which is 54% more expensive than the direct transportation of sawmill residues to the plant.
Figure 3.9: Transportation cost of sawmill residues to the district heating system

The numbers in brackets present the distance of the sawmill from the district heating system.
Table 3-15 includes the transportation cost of logging residues delivered directly or indirectly to the plant.

Table 3-15: Transportation cost of logging residues to the district heating system

<table>
<thead>
<tr>
<th>Transportation route</th>
<th>Transportation cost ($/Odt$^{-1}$)</th>
<th>Gavin Lake</th>
<th>Knife Creek</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood chips from roadside to plant</td>
<td>29.61</td>
<td>16.31</td>
<td></td>
</tr>
<tr>
<td>Wood chips from roadside to terminal storage</td>
<td>31.06</td>
<td>17.76</td>
<td></td>
</tr>
<tr>
<td>Wood debris from roadside to terminal storage</td>
<td>78.73</td>
<td>45.03</td>
<td></td>
</tr>
<tr>
<td>Wood chips from storage to plant</td>
<td>9.79</td>
<td>9.79</td>
<td></td>
</tr>
</tbody>
</table>

Direct transportation of wood chips from roadside to the plant costs $29.6 \text{ Odt}^{-1}$ for Gavin Lake residues and costs $16.31\text{ Odt}^{-1}$ for Knife Creek residues.

Since woodchips are transported with 53' high chip van and non-chipped residues are transported with 3 axle truck, indirect transportation cost depends on whether chipping takes place at roadside or at the terminal storage.

Table 3-16 includes transportation costs in different supply chain options for delivery of logging residues to the heating plant.

Table 3-16: Total transportation cost in different supply chain options for logging residues

<table>
<thead>
<tr>
<th>Supply chain option</th>
<th>Transportation cost ($/Odt$^{-1}$)</th>
<th>Gavin Lake</th>
<th>Knife Creek</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct flow</td>
<td>29.61</td>
<td>16.31</td>
<td></td>
</tr>
<tr>
<td>Flow through storage- Chipping at roadside</td>
<td>31.06+9.79=40.84</td>
<td>17.76+9.79=27.55</td>
<td></td>
</tr>
<tr>
<td>Flow through storage- Chipping at terminal storage</td>
<td>78.73+9.79=88.52</td>
<td>45.03+9.79=54.82</td>
<td></td>
</tr>
</tbody>
</table>
3.5.4 Total delivery cost of biomass to the heating plant

Delivery cost of biomass to the plant includes loading, chipping, storage, and transportation costs. Figure 3.10 to Figure 3.12 show this cost for different supply chain options.

- Total delivery cost of sawmill residues

Direct delivery of sawmill residues costs $43.41 Odt\(^{-1}\). The transportation cost\(^{21}\) accounts for 46% and has the largest contribution in the total delivery cost of sawmill residues to the plant. Loading and chipping costs contribute 31% and 23% of the total cost.

When sawmill residues are sent to the heating plant via storage, the total cost increases to $70.39 Odt\(^{-1}\). Comparing with the direct flow option, this supply chain has an additional storage cost, loading cost, and transportation cost. The additional loading cost occurs in the storage when the loader is used to homogenize the woodchips or loading woodchips to the haulage equipment. When biomass flow is via storage, the transportation cost contributes for 43% of the total cost followed by loading cost (38%), chipping cost (15%), and storage cost (4%), respectively.

\(^{21}\)Transportation cost is the average of the transportation costs from each sawmill to the plant.
Total delivery cost of logging residues

Depending on the supply chain option, delivery of logging residues from Gavin Lake block of UBC Alex Fraser Research Forest varies from $56.04 Odt$^{-1}$ to $128.47 Odt$^{-1}$. The most economical option is to chip biomass at the roadside and transport the woodchips to the plant directly. In this option, logging residues are pre-piled at the cost of $2.64 Odt$^{-1}$ (Bradley 2007). Depending on the source location, when logging residues are chipped at roadside and then the woodchips are transported to and stored at the terminal storage, the total cost is 40%-60% more expensive than when residues are stored at and chipped at roadside.

The most expensive option is to transport logging residues to the storage and having the chipping process at the storage location. The transportation cost of logging residues is significantly higher than that of sawmill residues and chips since the low bulk density of the loose debris results in meeting the volume capacity limit of the truck before meeting the weight capacity limit.
Figure 3.11: Total delivery cost of logging residues from Gavin Lake roadside to the district heating system

Figure 3.12: Total delivery cost of logging residues from Knife Creek roadside to the district heating system
Regardless of the supply chain option, it is always less expensive to deliver biomass to the plant from Knife Creek block than Gavin Lake because Knife Creek block is located within a closer distance to the plant. Total delivery cost of biomass from Knife Creek can be as low as $42.75 Odt$^{-1}$ when biomass is chipped at roadside and transported directly to the plant and can be as high as $94.77$ Odt$^{-1}$ when loose debris is transported to, stored, and chipped at the terminal storage. Delivering biomass from Knife Creek block is also less expensive than delivering sawmill residues either transported directly or via storage with in-storage chipping process.

3.5.5 Total delivery cost of natural gas to the heating plant

Natural gas is the main contender of biomass as an energy source for the district heating system. Natural gas is a reliable source of energy throughout the province in terms of its availability and its well-developed network and infrastructure. Thus, the total delivery cost of biomass to the plant should be comparable to the total delivery cost of natural gas. The provision cost of natural gas to the heating plant is calculated in this section.

The total delivery cost of natural gas to a commercial/institutional building consists of several of cost terms. Table 3-17 shows these cost terms and their values:

<table>
<thead>
<tr>
<th>Table 3-17: Natural gas business rates for inland regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source: FortisBC (2012)</td>
</tr>
</tbody>
</table>

| Basic charge ($\text{.day}^{-1}$)       | 4.358 |
| Delivery charge ($\text{.GJ}^{-1}$)    | 2.362 |
| Midstream charge ($\text{.GJ}^{-1}$)   | 1.032 |
| Cost of gas ($\text{.GJ}^{-1}$)        | 2.977 |

In order to calculate the total delivery cost ($\text{.GJ}^{-1}$) of natural gas, the basic charge ($\text{.day}^{-1}$) should be expressed in terms of $\text{.GJ}^{-1}$. For this purpose, Eq. (3-24) is used.

\[
\text{Basic charge ($\text{.GJ}^{-1}$)} = \frac{\text{Basic charge ($\text{.day}^{-1}$)} \times \text{Number of days in a month}}{\text{Average monthly energy demand (GJ)}}
\]  

(3-24)
The average monthly energy demand is calculated using Eq. (3-25):

\[
\text{Average monthly energy demand (GJ)} = \frac{\text{Annual energy demand (GJ)}}{12} \tag{3-25}
\]

Based on a 30-day, and the annual demand of 67,211 GJ of energy, the basic charge is $0.02 GJ⁻¹.

The total delivery cost of natural gas is calculated through Eq. (3-26) and equals $6.39 GJ⁻¹.

\[
\text{Total delivery cost of natural gas ($.GJ⁻¹)} = \text{Basic charge ($.GJ⁻¹)} + \text{Delivery charge ($.GJ⁻¹)} + \text{Midstream charge ($.GJ⁻¹)} + \text{Cost of gas ($.GJ⁻¹)} \tag{3-26}
\]

3.6 Sensitivity analysis

In this section, firstly the impact of variations in the availability of biomass and the heat demand on the ability of match supply and demand are assessed. Then, the variations of the storage capacity and therefore storage cost when the biomass availability changes are examined. Furthermore, the sensitivity of per unit total delivery cost ($.Odt⁻¹) of biomass is examined respective to the material cost, moisture content, and machine productivity.

3.6.1 Impact of variations in supply and demand on the ability of meeting the demand

Since the availability of local woody biomass supply and the heat demand are quantified using averages, a sensitivity analysis is performed here to examine the impact of variations of supply and demand on the ability of fulfilling the demand with the local available biomass. For this purpose, supply and demand are changed ±20% from the base case scenario.

Figure 3.13 shows the variations of demand and supply over the course of a year when supply is the same as the base case scenario, while the heat demand and consequently the fuel demand varies ±20% from the base case scenario. When the fuel demand increases by 20%, other than the months with biomass shortage in the base case scenario, in March also demand exceeds the supply. However, the annual available supply (85,349 GJ) still exceeds the annual fuel demand (80,653 GJ) and the demand for extra biomass can be met using the stored excess biomass in
other months. December does not have biomass shortage anymore when the heat demand decreased by 20% from the base case scenario.

Figure 3.13: Variation of supply and demand over year when heat demand changes by ±20%

Figure 3.14 illustrates the variation of supply and demand over the year when the available supply varies ±20% from the base case scenario. When biomass availability decreases by 20% from the base case scenario, there is biomass shortage in March in addition to the months with biomass shortage in the base case scenario. Yet, there is more than enough biomass to fulfill the fuel demand of the district heating system. When the biomass availability increases by 20%, there is no biomass shortage in December anymore.
3.6.2 Sensitivity of storage cost to availability of biomass

The availability of biomass affects the capacity of storage, and thus the storage cost. Table 3-18 explains the sensitivity of storage capacity and storage cost relative to the availability of biomass with ±20% change from the base case scenario. For this scenario, the unit cost of storage does not vary from the base case scenario either.

Storage capacity increases from 744 Odt to 844 Odt when the availability of biomass decreases by 20% from the base case scenario. The reason is that stock at terminal should be always enough to guarantee the safety stock at the terminal. Although there is more than enough biomass to meet the fuel demand of the district heating system when the local biomass quantity decreases by 20% from the base case scenario, the annual extra biomass is not enough to keep the inventory level at the terminal at the desired level of 325 Odt. Thus, an initial inventory is required to ensure the safety stock at the terminal. This initial inventory equals 337 Odt of biomass and should be built up before the plant starts operating. Although the capacity of the
storage increases when biomass availability decreases, the unit cost of storage does not vary from the base case scenario, because the quantity of material that the terminal storage keeps in a year increases too.

The capacity of storage decreases from 744 Odt to 699 Odt when the biomass availability increases 20% from the base case scenario.

Per unit cost of storage ($/Odt\textsuperscript{-1}) varies slightly when biomass availability changes by ±20% from the base case scenario. Since the share of storage cost in the total delivery cost is very low, the variations in the total delivery cost of biomass are negligible.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Storage capacity (Odt)</th>
<th>Storage cost ($/Odt\textsuperscript{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case scenario</td>
<td>744</td>
<td>2.90</td>
</tr>
<tr>
<td>20% decrease</td>
<td>844</td>
<td>2.83</td>
</tr>
<tr>
<td>20% increase</td>
<td>699</td>
<td>2.87</td>
</tr>
</tbody>
</table>

### Table 3-18: Sensitivity of storage capacity and storage cost to availability of biomass

#### 3.6.3 Sensitivity of total delivery cost to material cost

- **Sawmill residues cost**

Usually, sawmill residues can be obtained free of charge (Bradley 2007). In the base case scenarios, the wastes from sawmills have no cost; however, because the demand for sawmill residues for energy generation is increasing, these residues are turning into commodity and sawmill owners might tend to charge a fee for their wastes (Bradley 2007). Bradley (2007) stated that sawmill residue price may vary between $0 Odt\textsuperscript{-1} and $25 Odt\textsuperscript{-1}. Therefore, a sensitivity analysis has been performed to investigate the effect of the material cost on the total delivery cost of sawmill residues to the gate of the heating plant. In the sensitivity analysis, the price decreases by 20%, 40%, 60%, 80% and 100% from the maximum price of $30 Odt\textsuperscript{-1}, which is the amount that Atlantic Power pays to obtain sawmill residues. Figure 3.15 shows the variations in the total delivery cost of sawmill residues to the plant when material cost per Odt changes from $0 to $30.
When sawmill residues are delivered to the plant directly, the total delivery cost increases up to 69% as the biomass purchase price increases from $0 Odt\(^{-1}\) of base case scenario to $30 Odt\(^{-1}\).

The biomass purchase price has a lower impact on the total delivery cost when biomass transported via the storage rather than when it is delivered directly from sawmills to the plant. At the price of $30 Odt\(^{-1}\), the total delivery cost via storage is 43% more than when biomass is free of charge. The reason is the lower contribution of biomass purchase price in the total cost in transportation via storage option rather than direct flow option.

![Figure 3.15: Sensitivity of total delivery cost to material cost- Sawmill residues](image)
• Logging residues cost

In the base case scenario, the stumpage price, the price paid to the BC Government for logging publicly owned timber, is used as the purchase price of logging residues. Currently, the stumpage price in British Columbia is $0.25 m$^3$ solid (MOF 2011a). This fee equals $0.46$ Odt$^{-1}$ when the following conversion factors are applied: 1 solid m$^3$ of wood corresponds to 3 loose m$^3$ of loose wood and 1 loose m$^3$ of wood corresponds to 0.18 Odt of wood (Skea et al. 2009)\textsuperscript{22}. In the sensitivity analysis, the stumpage price is increased from $0.46$ Odt$^{-1}$ to $37$ Odt$^{-1}$ in five steps. The impact of stumpage price on the delivery cost has been examined for each individual supply chain option.

Figure 3.16 and Figure 3.17 illustrate the changes in the total delivery cost of logging residues from Gavin Lake and Knife Creek blocks to the plant under different supply chain options when biomass price increases from the base case scenarios.

\begin{figure}[h]
\includegraphics[width=\textwidth]{chart.png}
\caption{Figure 3.16: Sensitivity of total delivery cost to material cost- Gavin Lake logging residues}
\end{figure}

\textsuperscript{22} The conversion factors are the averages from seven case studies in Skea et al. (2009)
Variation in moisture content changes costs of loading, chipping, storage, and transportation when they are expressed in terms of $.Odt\(^{-1}\). Since the transportation cost is a function of biomass bulk density (3-23), the impact of moisture content on the bulk density is one important consideration. To assess the effect of moisture content on the delivery cost of biomass to the plant, moisture content of woodchips and their corresponding bulk density from Case 3 in Jafari Naimi et al. (2009) has been used to regress bulk density on moisture content. Eq. (3-27) explains the relationship between bulk density and moisture content.

\[
\text{Bulk density} = 155.1762 + 203.6547 \times \text{Moisture content} + \text{Error} \tag{3-27}
\]

Assuming this relation is also true for sawmill residues, the bulk density of residues is predicted for moisture contents 20% higher and lower than the moisture content in the base case scenarios.
Table 3-19 shows the data points used for sensitivity analysis for both sawmill residues and logging residues.

Table 3-19: Moisture content of residues, corresponding bulk density, and load weight for sensitivity analysis

<table>
<thead>
<tr>
<th>Change in moisture content</th>
<th>Moisture content (%)</th>
<th>Bulk density (kg/m³)</th>
<th>Load weight (Odt)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sawmill residues</td>
<td>Logging residues</td>
<td>Sawmill residues</td>
</tr>
<tr>
<td>-20%</td>
<td>24.41</td>
<td>23.66</td>
<td>204.89</td>
</tr>
<tr>
<td>Base case</td>
<td>30.52</td>
<td>29.58</td>
<td>215.29</td>
</tr>
<tr>
<td>20%</td>
<td>36.62</td>
<td>35.49</td>
<td>229.75</td>
</tr>
</tbody>
</table>

Since the moisture content does not exceed the threshold of 38% suggested in MacDonald (2011), the weight does not limit the payloads and the payloads used in Section 3.6.4 remains valid.

The results of sensitivity analysis to moisture content for sawmill residues and logging residues are summarized in Figure 3.18 and Figure 3.19. Variation in moisture content has the same effect on the total delivery cost of biomass when different supply chains are used.

Figure 3.18: Sensitivity of total delivery cost to moisture content- Sawmill residues
3.6.5 Sensitivity of total delivery cost to machine productivity

As it was explained, measuring the productivity of machine requires field studies and in the base case scenarios, the productivity of machines was set to 50% of their capacity. Figure 3.20 to Figure 3.22 illustrate the sensitivity of total delivery cost to machine productivity. The variations in loading and chipping costs are the same for sawmill residues and logging residues, however, the total delivery cost of biomass to the gate of the plant varies differently depending on the biomass source and the supply chain option.
Figure 3.20: Sensitivity of total delivery cost to machine productivity- Sawmill residues

Figure 3.21: Sensitivity of total delivery cost machine productivity- Gavin Lake logging residues
3.7 Discussion and conclusions

In this chapter the feasibility of exploiting local biomass for generating heat in a district heating system in downtown core of Williams Lake, BC was assessed. To examine this viability, two questions were answered:

(1) Is there enough biomass to fulfill the heat demand?

(2) How much does it cost to deliver the biomass to the heating plant?

To answer the first question, the monthly fuel demand of the district heating system was estimated and the monthly availability of biomass was quantified. The district heating system in this research has to generate 44,359 GJ of thermal energy to fulfill the space heat demand and hot water requirements of its end users. If the heating plant uses natural gas, at the boiler efficiency of 92.5% and energy content of 37 GJ.m$^{-3}$, 1,296 m$^3$ of natural gas should be delivered to the plant annually. This quantity of natural gas can be replaced by 3,572 Odt of forest
biomass. Assuming an average payload of 17 Odt for the chip van, this quantity of biomass can be transported to the plant in 211 truckloads.

On average, 4,552 Odt of biomass is available annually. This quantity of biomass produces 85,446 GJ of heat which is more than enough to meet the fuel demand of the district heating system (67,211 GJ). Although the annual available biomass is more than the annual fuel demand, the fuel demand in April, May, June, July, and December exceeds the fuel supply. Since these estimates were obtained using average data, sensitivity analysis were performed to assess how the variations in supply and demand might impact the feasibility of using forest biomass for regional heat generation in terms of biomass availability. The sensitivity analysis indicated that a 20% increase in heat demand or 20% decrease in availability of biomass would not cause the annual demand exceeds the annual supply.

To answer the second question, different supply chains that can be used to deliver biomass to the plant were identified, the required equipment was determined and the total delivery cost of biomass from various source locations was estimated.

The most economical biomass source to be exploited is the logging residues from Knife Creek block of UBC Alex Fraser Research forest with a total delivery cost of $42.75 Odt⁻¹. In comparison with other biomass sources in this work, this logging block is located within a closer distance from the heating plant. However, the quantity of biomass that this block can provide to the district heating system is never enough to meet the fuel demand on its own. Sawmill residues come second after Knife Creek logging residues with the total delivery cost of $43.42 Odt⁻¹ and Gavin Lake logging residues cost $56.04 Odt⁻¹ to be delivered to the plant. When a fabric structure terminal storage is used to store woodchips, the total delivery cost increases to $67.50 Odt⁻¹, $70.38 Odt⁻¹, and $80.80 Odt⁻¹ for Knife Creek logging residues, sawmill wastes, and Gavin Lake logging residues, respectively. The total delivery cost of logging residues increases to $94.77 Odt⁻¹ for Knife Creek residues and to $128.47 Odt⁻¹ for Gavin Lake residues when the residues are transported non-chipped to the terminal storage and the chipping process takes place at the terminal storage. This cost remains at $70.38 Odt⁻¹ for sawmill residues. The reason is that non-chipped sawmill residues are hauled to the terminal storage using the same vehicle that transports wood chips, while non-chipped logging residues are transported using a smaller
capacity vehicle. Low bulk density of the non-chipped residues results in high transportation cost.

Finally, the sensitivity of the total delivery cost of biomass to changes in input parameters, including material cost, moisture content, and productivity of machine was measured.

When the price of sawmill residues increases from $0 Odt⁻¹ to $30 Odt⁻¹, the total delivery cost increases by 70% for the direct flow and by 40% for the flow via storage. The maximum and minimum increase in the delivery cost of logging residues are by 85% and 45% when increasing the biomass price from $0.46 Odt⁻¹ to $37 Odt⁻¹ for direct flow and flow via storage, chipping at terminal options, respectively.

The sensitivity analysis with respect to moisture content showed that the lower the moisture content, the less expensive is the total delivering of biomass to the plant. Moisture content has the lowest impact on the transportation cost, whereas the variations in loading, chipping, and storage costs are the same when moisture content changes.

Finally, there is the potential to lower the total delivery cost by 17% by improving the machine productivity by 20% from the base case scenario, while decreased machine productivity would increase the loading and chipping costs by 25%.

The total cost of biomass to the gate of the heating plant ranges from $2.19 GJ⁻¹ to $6.59 GJ⁻¹ (at the average energy content of 19.5 GJ.Odt⁻¹ for logging residues and 18.13 GJ.Odt⁻¹ for sawmill residues) depending on the supply chain option. The provision cost of natural gas to the gate of the heating plant is $6.39 GJ⁻¹. This illustrates that there is the potential to provide the thermal energy to several end-users in Williams Lake by burning local biomass and at a reasonable price. The dependency of the total delivery cost of biomass on the supply chain option indicates the importance of finding an optimal supply chain under which the delivery cost is minimum while the heat demand in each month is fulfilled using the available supply.
4.1 Synopsis

It was concluded in Chapter 3 that the total delivery cost of forest biomass to the plant depends on the design of the supply chain. Although the least costly supply chain option was to chip biomass at source points and transport woodchips directly to the plant, low availability of biomass and accessibility of forest areas in spring urged the inclusion of storage in the supply chain. On the other hand, transferring all the biomass to the plant through the terminal storage increased the logistics costs. There is a potential to reduce costs by transporting the biomass to the plant using a combination of the supply chain options.

In this chapter, the goal is to determine the optimal quantity of biomass that flows through each of supply chain options to minimize the total cost of supplying biomass to the heating plant. For this purpose, the model developed by Gunnarsson et al. (2004) is modified into a linear programming model and applied to the case study in the present study. The objective of this model is to minimize the total annual cost of delivering forest biomass to the gate of the heating plant. The model has constraints related to the availability of biomass, heat demand, chipping and storage capacities. The model in Gunnarsson et al. (2004) includes binary variables to select among biomass suppliers and also to select among several terminal storages to transport biomass to the heating plants. The model in the present work is the simplified form of Gunnarsson et al. (2004); it includes one terminal storage facility and one heating plant. The objective functions and constraints of these models are similar. The model in this research prescribes the solution to the following question: How much biomass should be transported from each potential supply chain source in each month?
4.2 Model structure

Mathematical models are systems of equations and mathematical notations that abstract the problem of concern (Hillier et al. 1990). Therefore, the very first step in mathematical programming is to define the problem of interest. This step includes the determination of objectives, restrictions, alternative actions and so on. Afterwards, the problem should be formulated using mathematical language (Hillier et al. 1990). A mathematical model is built on four key components (Kallrath 2004):

1) **Parameters** are the constants of the problem such as demand, cost, capacity, and so on. Constant are used in constraints (3) and the objective function (4).

2) **Decision variables** are quantifiable unknowns of the model; the model determines the optimum value of these variables. Occasionally, decision variables measure the amount of resources to exploit, or the level of some activities to be performed (Russel et al. 2003). Variables might be continuous, semi-continuous, integer or binary (Kallrath 2004).

3) **Constraints** are relationships of decision variables expressed through mathematical equalities or inequalities and restrict the range of values that decision variables can take. Decision variables might be restricted by limited resources or limiting guidelines (Hillier et al. 1990).

4) **Objective function** is the goal of the decision making process such as maximizing profit, maximizing utilization rate, minimizing cost, minimizing waste, and so on. Objective function is a function of decision variables (Hillier et al. 1990).

Based on their structure, mathematical models can be linear, mixed integer linear, nonlinear, and mixed integer nonlinear programming models (Kallrath 2004). In a linear programming model, constraints and objective function are linear relationships of decision variables (Russel et al. 2003). The modified model is explained below and Figure 4.1 illustrates the schematic view of this model.
Figure 4.1: Schematic view of the modified model
4.2.1 **Parameters**

- $S_{it}$: Quantity of residues available at source point $i$ at time $t$
- $D_{kt}$: Fuel demand of plant $k$ at time $t$
- $C_{ai}$: Chipping capacity in month $t$
- $E$: Chipping efficiency
- $SC_{j}^{tot}$: Total storage capacity of the terminal $(j)$
- $SS_{jt}$: Safety stock at the terminal $(j)$ in month $t$
- $C_{ij}^{N}$: Unit transportation cost of non-chipped products from source $i$ to the terminal $(j)$
- $C_{ij}^{c}$: Unit transportation cost of chipped products from source point $i$ to the terminal $(j)$
- $C_{jk}^{c}$: Unit transportation cost of chipped products from the terminal $(j)$ to the plant $(k)$
- $C_{ik}^{c}$: Unit transportation cost of chipped products from source $i$ to the plant $(k)$
- $C_{i}^{l}$: Unit loading cost of residues at source $i$
- $C_{j}^{l}$: Unit loading cost of residues at the terminal $(j)$
- $C_{i}^{c}$: Unit chipping cost of residues at source $i$
- $C_{j}^{c}$: Unit chipping cost of residues at the terminal $(j)$
- $C_{i}^{P}$: Unit purchase price of residues at source $i$
- $C_{j}^{ts}$: Unit cost of storing residues at the terminal $(j)$
- $C_{i}^{rs}$: Unit cost of storing residues at source point $i$

4.2.2 **Decision variables**

- $q_{it}^{F}$: Quantity of forest residues chipped at source point $i$ at time $t$
- $q_{jt}^{F}$: Quantity of forest residue chipped at the terminal $(j)$ at time $t$
- $q_{ijt}^{c}$: Quantity of chipped products transported from source point $i$ to the terminal $(j)$ at time $t$
Quantity of chipped products transported from the terminal (j) to the plant (k) at time t
$\mathbf{q}_{ikt}^c$

Quantity of chipped products transported from source point i to the plant (k) at time t
$\mathbf{q}_{ikt}^c$

Quantity of chipped products stored at the terminal (j) at time t
$\mathbf{t}_jt^c$

Quantity of non-chipped products transported from source point i to the terminal (j) at time t
$\mathbf{q}_{ijt}^N$

Quantity of non-chipped products stored at the terminal (j) at time t
$\mathbf{t}_jt^N$

Quantity of non-chipped products stored at roadside i at time t
$\mathbf{r}_{it}^N$

4.2.3 Constraints

(1) Balancing constraint for non-chipped products at source points

In each time period, new biomass is forwarded to the roadside ($S_{it}$) and is added to the biomass stored at the source location in previous time periods ($r_{it,t-1}^N$). Constraint (4-1) explains that the total biomass stored at source location ($r_{it}^N$), chipped at source location ($q_{ijt}^c$), and sent to the terminal ($q_{ijt}^c$) has to be equal to the total available biomass at each time period. This constraint also ensures that the quantity of biomass that is chipped at each source location does not exceed the available supply at each time period.

$$r_{it,t-1}^N + S_{it} = r_{it}^N + q_{ijt}^c + q_{ijt}^c \quad \forall i \in I, \forall t \in T$$  \hspace{1cm} (4-1)

(2) Balancing constraint for chipped products at source points

Constraint (4-2) ensures that the biomass that is chipped at the source point is either sent directly to the heating plant or to the terminal storage within the same period it is chipped. Since $q_{pit}$ indicates the amount of residue to be chipped, and $q_{ijt}^c$ and $q_{ikt}^c$ indicate the quantity of chipped products, efficiency of chipping product should be incorporated in this constraint.

$$q_{pit}^c \times E = q_{ijt}^c + q_{ikt}^c \quad \forall i \in I, \forall t \in T$$  \hspace{1cm} (4-2)
(3) Balancing constraint for non-chipped product at terminals

Constraint (4-3) indicates that in each time period, new biomass transported from the source points to the terminal storage ($\sum_{i} q^{N}_{ijt}$) accumulates over the non-chipped biomass stored there in previous time periods ($ts^{N}_{jt\_t-1}$). The total biomass available in each time period at the terminal storage is stored non-chipped ($ts^{N}_{jt}$) or chipped ($q^{F}_{jt}$).

$$ts^{N}_{jt\_t-1} + \sum_{i} q^{N}_{ijt} = ts^{N}_{jt} + q^{F}_{jt} \quad \forall \ t \in T$$  \hspace{1cm} (4-3)

(4) Balancing constraint for chipped products at terminals

In each time period the amount of chipped products at the terminal equals the stored chipped products at previous time periods, new chipped products transported from source points, and biomass that is chipped at terminal storage in that time period. This total amount of chips is stored or transported to the heating plant. This restriction is expressed through constraint (4-4):

$$ts^{c}_{jt\_t-1} + \sum_{i} q^{c}_{ijt} + q^{F}\times E = ts^{c}_{jt} + q^{c}_{jkt} \quad \forall \ t \in T$$  \hspace{1cm} (4-4)

(5) Chipping Capacity constraint

The total volume that can be chipped at each time period cannot exceed the monthly chipping capacity. Constraints (4-5) and (4-6) indicate the capacity restriction of the chipping process at the source points and at the terminal storage, respectively.

$$\sum_{i} q^{F}_{it} \times E \leq Ca_{i} \quad \forall \ t \in T$$  \hspace{1cm} (4-5)

$$q^{F}_{jt} \times E \leq Ca_{jt} \quad \forall \ t \in T$$  \hspace{1cm} (4-6)
(6) Storage capacity constraint

The total biomass sent to and stored at the terminal storage in any form chipped and non-chipped must not exceed the total storage capacity of the terminal storage. Restriction on storage capacity is expressed using Eq. (4-7).

\[ SS_{jt} \leq ts_{jt}^{c} + ts_{jkt}^{N} \leq SC_{j}^{t} \quad \forall t \in T \]  

(4-7)

(7) Heat demand constraint

The fuel demand of the heating plant should be fulfilled in each time period. Constraint (4-8) explains the heat demand constraint and restricts the flow of material to the plant based on the fuel demand of the plant.

\[ \sum_{i} q_{ikt}^{c} + q_{jkt}^{c} = D_{kt} \quad \forall t \in T \]  

(4-8)

4.2.4 Objective function

The objective of this mathematical model is to minimize the annual total cost of biomass delivery cost to the heating plants. Eq. (4-9) defines the total delivery cost:

Min Total cost \((Z) = \text{Material cost (} C^{p} \text{)} + \text{Loading cost (} C^{l} \text{)} + \text{Chipping cost (} C^{c} \text{)} + \text{Transportation cost (} C^{t} \text{)} + \text{Storage cost (} C^{s} \text{)} \)  

(4-9)

Cost terms are explained in Eq. (4-10) to Eq. (4-14).

\[ C^{p} = \sum_{i} \sum_{t} C_{i}^{p} \times \frac{(q_{ikt}^{c} + q_{jkt}^{c})}{E} \]  

(4-10)

\[ C^{l} = \sum_{i} \sum_{t} C_{i}^{l} \times q_{pit}^{F} + \sum_{t} C_{j}^{l} \times (q_{jkt}^{F} + ts_{jkt}^{N}) \]  

(4-11)
\[
\begin{align*}
C^C &= \sum_i \sum_t C_i^c \times q_{it} + \sum_t C_t^c \times q_{jt}^F \quad (4-12) \\
C^t &= \sum_i \sum_t C_{ij}^N \times q_{ijt}^N + C_i^c \times q_{ijt}^C + \sum_t C_{jk}^c \times q_{jkt} + \sum_t C_{ik}^c \times q_{ikt}^c \quad (4-13) \\
C^s &= \sum_i \sum_t C_i^{rs} \times r_{pit}^N + \sum_t C_t^{ts} \times (ts_{jt}^c + ts_{jt}^N) \quad (4-14)
\end{align*}
\]

4.3 Model input data

(1) Demand \((D_{kt})\) and supply \((S_{pit})\)

Biomass produced at each source point and the fuel demand of the heat plant at each time period were calculated in Chapter 3. Table 4-1 shows the input data for demand \((D_{kt})\), and supply \((S_{pit})\) respectively.

Table 4-1: Input data for supply quantity at source point i and demand at plant (Odt) at time period t

<table>
<thead>
<tr>
<th>Source point (i)</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
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<td>8</td>
<td>1</td>
<td>-</td>
<td>3</td>
<td>30</td>
<td>65</td>
<td>92</td>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td>Gavin Lake</td>
<td>367</td>
<td>324</td>
<td>62</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>117</td>
<td>182</td>
<td>152</td>
<td>160</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>Knife Creek</td>
<td>137</td>
<td>201</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>136</td>
<td>59</td>
<td>59</td>
</tr>
<tr>
<td>Fuel demand</td>
<td>516</td>
<td>416</td>
<td>390</td>
<td>325</td>
<td>182</td>
<td>145</td>
<td>95</td>
<td>110</td>
<td>176</td>
<td>279</td>
<td>342</td>
<td>595</td>
</tr>
</tbody>
</table>
(2) Capacity and efficiency constants

The storage capacity \( (SC_{10}^{\text{tot}}) \) was calculated as 744 Odt in Section 3.5.3, Page 60. In the same section, it was discussed that the stock at the terminal always should be equal or greater than a safety stock level of 100 Odt in July, August, and September and 325 Odt in the other months. In the terminal storage capacity constraint, the storage capacity was considered as the upper bound and the terminal safety stock was considered as the lower bound of the constraint.

The average chipping capacity for one mobile chipper can be obtained using Eq. (4-15).

\[
\bar{C_a} = \frac{\text{Chipper output capacity (GMT.PMH}^{-1}) \times \text{PMH yr}^{-1}}{12}
\]  

(4-15)

For this case study the chipper output capacity is 38 GMT.PMH\(^{-1}\); considering that there are 900 productive machine hours in a year, this chipper can produce an average quantity of 2850 GMT per month. However, there is no access to Gavin Lake and Knife Creek blocks in the 3 months period from March 15\(^{th}\) to June 15\(^{th}\). To make adjustments to this condition, the chipping capacity for the months of March and June at these locations is considered as half of the capacity calculated above, while for the months of April and May the chipping capacity is set to zero.

The calculations in Chapter 3 showed that one chipper can handle the mass forecasted for the demand. Since the biomass piles are small and scattered over a large area, the chipper has to move over large distances. Taking into account shut downs for maintenance, breakdowns, and also the extra work that the chipper has to do to cover the wood chips demand of the months with no or restricted access to forest areas, two chippers are considered herein. One of the chippers is assigned to the terminal storage and the other one is assigned to the source points.

The monthly chipping capacity of the chipper moving between sources is distributed among source points based on the availability of biomass at each source point. Eq. (4-16) expresses the monthly chipping capacity.

\[
C_{a_{it}} = \frac{S_{it}}{\sum_i S_{it}} \times \bar{C_a}
\]  

(4-16)
where $C_{at}$ (Odt) is the chipping capacity at source point i at time t, $S_{it}$ (Odt) is the supply available at location i at the end of time period t. $\bar{C}_a$ is the average monthly chipping capacity at time period t. Table 4-2 illustrates the input data used for chipping capacity for the optimization model.

Table 4-2: Input data for monthly chipping capacity (Odt)

<table>
<thead>
<tr>
<th>Source point (i)</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gavin Lake</td>
<td>779</td>
<td>762</td>
<td>138</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1,047</td>
<td>922</td>
<td>874</td>
<td>588</td>
<td>649</td>
</tr>
<tr>
<td>Knife Creek</td>
<td>291</td>
<td>473</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>499</td>
<td>239</td>
<td></td>
<td></td>
</tr>
<tr>
<td>62A</td>
<td>26</td>
<td>19</td>
<td>-</td>
<td>116</td>
<td>-</td>
<td>507</td>
<td>-</td>
<td>21</td>
<td>33</td>
<td>15</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>62C</td>
<td>165</td>
<td>159</td>
<td>257</td>
<td>74</td>
<td>245</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>62F</td>
<td>351</td>
<td>204</td>
<td>187</td>
<td>662</td>
<td>290</td>
<td>768</td>
<td>1,005</td>
<td>366</td>
<td>271</td>
<td>367</td>
<td>93</td>
<td>217</td>
</tr>
<tr>
<td>62V</td>
<td>42</td>
<td>129</td>
<td>241</td>
<td>495</td>
<td>330</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>51</td>
<td>206</td>
</tr>
<tr>
<td>6FD</td>
<td>43</td>
<td>27</td>
<td>98</td>
<td>330</td>
<td>-</td>
<td>-</td>
<td>128</td>
<td>128</td>
<td>-</td>
<td>95</td>
<td>23</td>
<td>63</td>
</tr>
<tr>
<td>6L2</td>
<td>21</td>
<td>37</td>
<td>97</td>
<td>89</td>
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<td>376</td>
<td>540</td>
<td>76</td>
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<td>16</td>
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<td>55</td>
</tr>
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<td>6T2</td>
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<td>105</td>
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<td>321</td>
<td>115</td>
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</tr>
<tr>
<td>C80</td>
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<td>101</td>
<td>-</td>
<td>330</td>
<td>-</td>
<td>123</td>
<td>39</td>
<td>172</td>
<td>195</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C85</td>
<td>158</td>
<td>100</td>
<td>556</td>
<td>108</td>
<td>57</td>
<td>-</td>
<td>114</td>
<td>262</td>
<td>324</td>
<td>518</td>
<td>217</td>
<td>118</td>
</tr>
<tr>
<td>total</td>
<td>1,995</td>
<td>1,997</td>
<td>1,846</td>
<td>1,979</td>
<td>1,967</td>
<td>1,980</td>
<td>1,980</td>
<td>1,994</td>
<td>1,993</td>
<td>1,992</td>
<td>1,995</td>
<td>1,992</td>
</tr>
</tbody>
</table>

(3) Transportation costs

Unit transportation costs ($.Odt^{-1}) from the source points to the terminal and to the plant and also from the terminal to the plant was calculated using Eq. (3-22). Table 4-3 compiles the transportation costs.
Table 4-3: Transportation cost ($/Odt$)

<table>
<thead>
<tr>
<th>Residue type</th>
<th>Non-Chipped</th>
<th>Chipped</th>
<th>Chipped</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source point (i)</td>
<td>From source to terminal ($C^i_{ji}$)</td>
<td>From source to terminal ($C^i_{ij}$)</td>
<td>From source to plant ($C^i_{jk}$)</td>
</tr>
<tr>
<td>Gavin Lake</td>
<td>78.73</td>
<td>31.06</td>
<td>29.61</td>
</tr>
<tr>
<td>Knife Creek</td>
<td>45.03</td>
<td>17.76</td>
<td>16.31</td>
</tr>
<tr>
<td>62A</td>
<td>9.80</td>
<td>9.80</td>
<td>8.57</td>
</tr>
<tr>
<td>62C</td>
<td>13.47</td>
<td>13.47</td>
<td>12.00</td>
</tr>
<tr>
<td>62F</td>
<td>11.51</td>
<td>11.51</td>
<td>9.80</td>
</tr>
<tr>
<td>62V</td>
<td>31.84</td>
<td>31.84</td>
<td>30.37</td>
</tr>
<tr>
<td>6FD</td>
<td>25.23</td>
<td>25.23</td>
<td>23.76</td>
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<tr>
<td>6L2</td>
<td>18.62</td>
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<td>16.90</td>
</tr>
<tr>
<td>6T2</td>
<td>12.98</td>
<td>12.98</td>
<td>12.98</td>
</tr>
<tr>
<td>C80</td>
<td>31.60</td>
<td>31.60</td>
<td>30.13</td>
</tr>
<tr>
<td>C85</td>
<td>34.78</td>
<td>34.78</td>
<td>33.31</td>
</tr>
</tbody>
</table>

Transportation cost of wood chips from terminal storage to heating plant ($C^i_{jk}$) 9.55

(4) Purchasing and processing costs

The unit chipping and loading costs ($/Odt$) were calculated in Section 3.5.3., Page 56. Unit loading and chipping cost at terminal is the average of unit loading and chipping costs of sawmill residues and logging residues because these residues are handled and processed together at terminal storage. Table 4-4 contains input data for material cost and different processing costs.

Table 4-4: Purchasing and processing costs

<table>
<thead>
<tr>
<th>Source point (i)</th>
<th>Purchase cost ($/Odt$)</th>
<th>Loading cost ($/Odt$)</th>
<th>Chipping cost ($/Odt$)</th>
<th>Roadside storage cost ($/Odt$)</th>
<th>Terminal storage cost ($/Odt$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sawmills</td>
<td>0.00</td>
<td>13.44</td>
<td>10.21</td>
<td>0.00</td>
<td>2.90</td>
</tr>
<tr>
<td>Logging blocks</td>
<td>0.46</td>
<td>13.26</td>
<td>10.07</td>
<td>2.64</td>
<td>2.90</td>
</tr>
</tbody>
</table>
4.4 Model outputs

The linear programming model has been solved using the AIMMS 3.11™ software (Paragon Decision Technology 2010).

The optimization model achieved the following optimal solution for the delivering cost of forest biomass feedstock to the gate of the heating plant.

Table 4-5: Optimal solution of the LP model

<table>
<thead>
<tr>
<th>Cost component</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>$1,116.00</td>
</tr>
<tr>
<td>Loading</td>
<td>$48,901.00</td>
</tr>
<tr>
<td>Chipping</td>
<td>$37,143.00</td>
</tr>
<tr>
<td>Storage</td>
<td>$9,612.00</td>
</tr>
<tr>
<td>Transportation</td>
<td>$79,582.00</td>
</tr>
<tr>
<td>Total annual cost (Z)</td>
<td>$176,404.00</td>
</tr>
</tbody>
</table>

The LP model also found an optimal monthly plan to exploit regional forest biomass. In each time period, available biomass is chipped at the source point, sent to the terminal storage, or left non-chipped at the source. Table 4-6 presents the optimal results for the quantity of biomass that should be chipped at each source point at the end of each month.
Table 4-6: Optimum quantity (Odt) of biomass chipped at source points in each month

<table>
<thead>
<tr>
<th>Source point (i)</th>
<th>Month</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Jan</td>
<td>Feb</td>
<td>Mar</td>
<td>Apr</td>
<td>May</td>
<td>Jun</td>
<td>Jul</td>
<td>Aug</td>
<td>Sep</td>
<td>Oct</td>
<td>Nov</td>
<td>Dec</td>
</tr>
<tr>
<td>Gavin Lake</td>
<td>367</td>
<td>245</td>
<td>142</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>117</td>
<td>180</td>
<td>154</td>
<td>31</td>
<td>-</td>
</tr>
<tr>
<td>Knife Creek</td>
<td>137</td>
<td>201</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>136</td>
<td>59</td>
<td></td>
</tr>
<tr>
<td>62A</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>41</td>
<td>-</td>
<td>-</td>
<td>10</td>
<td>4</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>62c</td>
<td>79</td>
<td>-</td>
<td>127</td>
<td>5</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>62F</td>
<td>127</td>
<td>-</td>
<td>29</td>
<td>180</td>
<td>-</td>
<td>34</td>
<td>28</td>
<td>29</td>
<td>-</td>
<td>62</td>
<td>95</td>
<td>54</td>
</tr>
<tr>
<td>62V</td>
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<td>-</td>
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<td>-</td>
<td>105</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6Fd</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>79</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>50</td>
<td>-</td>
<td>29</td>
</tr>
<tr>
<td>6L2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>60</td>
<td>9</td>
<td>15</td>
<td>-</td>
<td>-</td>
<td>12</td>
<td>24</td>
<td>14</td>
</tr>
<tr>
<td>6T2</td>
<td>39</td>
<td>-</td>
<td>-</td>
<td>69</td>
<td>17</td>
<td>-</td>
<td>9</td>
<td>13</td>
<td>-</td>
<td>-</td>
<td>61</td>
<td>120</td>
</tr>
<tr>
<td>C80</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>65</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
<td>C85</td>
<td>76</td>
<td>-</td>
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<td>-</td>
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<td>-</td>
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<td>844</td>
<td>446</td>
<td>400</td>
<td>334</td>
<td>187</td>
<td>149</td>
<td>52</td>
<td>159</td>
<td>180</td>
<td>286</td>
<td>351</td>
<td>276</td>
</tr>
</tbody>
</table>

Table 4-7 includes the quantity of biomass that should be stored at source points in each time period.

Table 4-7: Optimum quantity (Odt) of biomass stored at source points

<table>
<thead>
<tr>
<th>Source point (i)</th>
<th>Month</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Jan</td>
<td>Feb</td>
<td>Mar</td>
<td>Apr</td>
<td>May</td>
<td>Jun</td>
<td>Jul</td>
<td>Aug</td>
<td>Sep</td>
<td>Oct</td>
<td>Nov</td>
<td>Dec</td>
</tr>
<tr>
<td>Gavin Lake</td>
<td>-</td>
<td>79</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>129</td>
<td>290</td>
</tr>
<tr>
<td>Knife Creek</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>62A</td>
<td>13</td>
<td>21</td>
<td>21</td>
<td>29</td>
<td>29</td>
<td>-</td>
<td>-</td>
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<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>62C</td>
<td>-</td>
<td>69</td>
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<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
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<tr>
<td>62F</td>
<td>40</td>
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<td>141</td>
<td>10</td>
<td>16</td>
<td>-</td>
<td>-</td>
<td>12</td>
<td>66</td>
<td>70</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>62V</td>
<td>-</td>
<td>56</td>
<td>62</td>
<td>98</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>14</td>
<td>66</td>
</tr>
<tr>
<td>6Fd</td>
<td>20</td>
<td>32</td>
<td>55</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>14</td>
<td>40</td>
<td>7</td>
<td>13</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6L2</td>
<td>10</td>
<td>26</td>
<td>48</td>
<td>55</td>
<td>-</td>
<td>-</td>
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<td>6T2</td>
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<td>-</td>
<td>41</td>
<td>49</td>
<td>57</td>
<td>-</td>
<td>-</td>
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<tr>
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<td>34</td>
<td>57</td>
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<td>57</td>
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<td>-</td>
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<td>130</td>
<td>160</td>
<td>225</td>
<td>316</td>
<td>376</td>
<td>406</td>
</tr>
</tbody>
</table>
When the biomass is chipped at source the woodchips are transported to either the terminal storage or the heating plant. Table 4-8 illustrates the monthly quantity of woodchips that is transported from source points to the terminal. There is no flow of woodchips from the source points to the terminal in the other months.

<table>
<thead>
<tr>
<th>Source point (i)</th>
<th>Jan</th>
<th>Feb</th>
<th>Jun</th>
<th>Oct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gavin Lake</td>
<td>155</td>
<td>-</td>
<td>-</td>
<td>102</td>
</tr>
<tr>
<td>Knife Creek</td>
<td>134</td>
<td>19</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>62A</td>
<td>-</td>
<td>-</td>
<td>12</td>
<td>-</td>
</tr>
<tr>
<td>6T2</td>
<td>38</td>
<td>-</td>
<td>-</td>
<td>49</td>
</tr>
</tbody>
</table>

The transported woodchips to the terminal storage might be sent to the district heating system within the same month or stored in the terminal. Table 4-9 contains the quantity of biomass that is stored in the terminal storage and Table 4-10 illustrates the monthly flow of wood chips from the storage to the heating plant.

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>307</td>
<td>326</td>
<td>326</td>
<td>326</td>
<td>314</td>
<td>181</td>
<td>163</td>
<td>163</td>
<td>163</td>
<td>326</td>
<td>326</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4-11 demonstrates the monthly flow of biomass from the source points to the heating plant.
### Table 4-11: Optimum quantity (Odt) of woodchips transported from source points to the heating plant

<table>
<thead>
<tr>
<th>Source point (i)</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gavin Lake</td>
<td>203</td>
<td>239</td>
<td>138</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>82</td>
<td>176</td>
<td>150</td>
<td>30</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Knife Creek</td>
<td>-</td>
<td>177</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>132</td>
<td>58</td>
<td>-</td>
</tr>
<tr>
<td>62A</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>40</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>10</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>62C</td>
<td>77</td>
<td>-</td>
<td>124</td>
<td>5</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>62F</td>
<td>124</td>
<td>-</td>
<td>29</td>
<td>176</td>
<td>-</td>
<td>33</td>
<td>27</td>
<td>28</td>
<td>-</td>
<td>60</td>
<td>93</td>
<td>53</td>
</tr>
<tr>
<td>62V</td>
<td>20</td>
<td>48</td>
<td>-</td>
<td>102</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6Fd</td>
<td>-</td>
<td>-</td>
<td>77</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>49</td>
<td>-</td>
<td>-</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>6L2</td>
<td>20</td>
<td>48</td>
<td>-</td>
<td>102</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6T2</td>
<td>-</td>
<td>-</td>
<td>68</td>
<td>16</td>
<td>-</td>
<td>9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>60</td>
<td>117</td>
<td>-</td>
</tr>
<tr>
<td>C80</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>63</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C85</td>
<td>74</td>
<td>51</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The optimization results show that the optimal solution does not include the flow via terminal storage and chipping residues at the storage. High transportation cost of non-chipped residues because of their low bulk density can justify this. Only 10.16% of the total annual flow of woodchips to the plant is via storage, the rest 90.34% is transported directly to the plant. The flow via terminal storage takes place in January, May, June, July, and December.

#### 4.5 Sensitivity analysis

This section examines the variations of the optimal solution when (1) biomass purchase price (2) availability of biomass, and (3) heat demand change.

##### 4.5.1 Sensitivity to material cost

When sawmill residues price increases from $0 Odt\(^{-1}\) to $30 Odt\(^{-1}\), the total annual delivery cost increases by 36% from the base case scenario (Figure 4.2). For sawmill residue prices more than $6 Odt\(^{-1}\), loading, chipping, storage, and transportation costs are constant and only the material cost increases.
When logging residues purchase price increases from $0.46 Odt\(^{-1}\) to $37 Odt\(^{-1}\), the total annual cost of biomass delivery to the heating plant increases by 36% (Figure 4.3).

![Figure 4.2: Sensitivity of optimal solution to sawmill residues cost](image)

![Figure 4.3: Sensitivity of optimal solution to logging residues cost](image)
4.5.2 Sensitivity to biomass availability

When biomass availability decreases by 20% at all the locations, the problem turns infeasible. In Section 3.6.2 (Page 72), the sensitivity of the storage cost to the availability of biomass highlighted that when the biomass availability decreases by 20% from the base case scenario, the annual demand still exceeds the annual supply quantity. However, the extra biomass is not enough to keep the storage level at safety stock level and to meet the demand at the same time. This can justify the infeasibility of the problem when biomass availability decreases by 20% from the base case scenario. The problem remains infeasible for decrease levels more than 11%. Figure 4.4 illustrates the impact of biomass availability variations on the total annual cost.

Roughly, the annual total cost of delivering biomass to the plant and biomass availability vary in the opposite directions. When more biomass is available, material cost and storage cost increase because for the case with more biomass quantities, the flow of biomass from knife Creek increases. Since logging residues cost $0.46 Odt$^{-1}$ the annual material cost increases. Meanwhile, the annual transportation cost decreases because of the short distance between this block and the terminal storage and the heating plant. Since transportation cost has a high contribution in the total cost, the increase in the material and storage costs is offset by the decrease in the transportation cost.

4.5.3 Sensitivity to heat demand

Figure 4.5 demonstrates the sensitivity of the total annual cost to the heat demand when it changes ± 20% from the base case scenario.

The total annual cost and the heat demand changes are in the same direction. For this problem to be feasible, the maximum level of increase in the heat demand is 14%. Increases of more than 9% in the heat demand would make the problem infeasible.
Figure 4.4: Sensitivity of optimal solution to biomass availability

Figure 4.5: Sensitivity of optimal solution to heat demand
4.6 Discussion and conclusions

This chapter presented a linear programming model to determine the optimal flow of biomass between nodes of the supply network including biomass source points, terminal storage and the heating plant. The objective of this optimization model was to minimize the annual total cost including material cost, loading cost, chipping cost, roadside and terminal storage costs, and transportation cost. The constraints in this model were supply, demand, storage capacity, and chipping capacity. The results indicated that it would cost $177,404.00 per year to supply forest biomass to the district heating system. The transportation cost contributed to 45.11% of the annual total cost followed by loading cost (27.72%), chipping cost (21.06%), storage cost (5.45%), and material cost (0.66%), respectively.

Sensitivity of the annual total cost was examined with respect to the material cost, availability of biomass, and heat demand. The summary of the sensitivity analysis are as follow:

1. Sensitivity analysis with respect to the material cost showed that increase in the purchase price of forest biomass could result in increase in the annual total cost up to 36% when logging residue price increased to $37 Odt\(^{-1}\) and sawmill residue price increased to $30 Odt\(^{-1}\).
2. Sensitivity analysis with respect to biomass availability showed that higher availability of biomass favours the lower delivery cost of forest biomass. An important conclusion in this analysis was that when biomass decreased more than 11% from the base case scenario, the problem would not be feasible any more.
3. The sensitivity analysis toward heat demand demonstrated that the cost of delivering forest biomass to the gate of heating plant increased when heat demand increased. Also, when heat demand increased more than 14% from the base case scenario, the problem would not be feasible.
Chapter 5. Conclusions, limitations, and future research directions

5.1 Conclusions

This thesis examined the feasibility of using local forest biomass as an energy source for district heat generation in Williams Lake, BC. To address this goal, (1) the availability of forest biomass including logging residues and sawmill wastes was quantified; (2) the machines and equipment for handling, processing, and transporting biomass to the destination were identified; (3) the supply chain options for delivering forest biomass to the heating plant was determined; (4) the cost of delivering forest biomass to the plant was calculated for each supply chain option; and (5) the optimum design of the supply chain was determined.

The results of the feasibility study in Chapter 3 indicated that the annual total biomass supply, 4552 Odt, exceeds the annual fuel demand 3,572 Odt; nevertheless, matching demand and supply is challenging since biomass availability fluctuates substantially over the time and in some months of the year biomass sources are not accessible. The chasm between the supply side and the demand side suggests the use of a terminal storage to store the biomass from the months with extra supply for the months with extra demand. Delivering forest biomass to the district heating system might cost as low as $42.75 Odt$^{-1}$ ($2.19 \text{ GJ}^{-1}$) and as high as $128.47 \text{Odt}^{-1}$ ($6.59 \text{ GJ}^{-1}$) depending on the design of the supply chain and the location of biomass source.

For this case study, the least expensive supply chain is the direct flow of woodchips from source points to the heating plant followed by forwarding woodchips to the terminal storage and then from the terminal storage to the heating plant. The most expensive supply design is when wood residues are transported to the terminal storage, chipped at the terminal storage, and finally wood chips are transported from the terminal storage to the heating plant. Regardless of the supply chain design, the transportation cost has the highest contribution in the total delivery cost of biomass followed by, loading, chipping, and material costs, respectively. For the supply chain options with terminal storage, the storage cost has a higher contribution in the total cost than the material cost.

Gautam et al. (2010) calculated the cost of delivering forest biomass to the gate of a CHP plant in Ontario using a direct supply chain including felling, skidding, loading, grinding, and
transporting. In their study, the delivery cost of biomass to the heating plant totalled $40.21 \text{ Odt}^{-1} or $2.17 \text{ GJ}^{-1}$ using a general inflation rate of 1.96\% per year. MacDonald (2009) estimated the total cost of delivering woodchips to an end user in British Columbia. The total cost included loading, chipping, and transportation costs and was equal to $64.80 \text{ Odt}^{-1}$. Skea et al. (2009) also calculated the total cost of delivering biomass to end users in seven case studies in Williams Lake, BC. The total cost in their study included loading, chipping, and hauling costs and ranged from $40.90 \text{ Odt}^{-1}$ to $153.81 \text{ Odt}^{-1}$. In this thesis, the delivery cost of forest biomass to the heating plant was found to be in the range of $42.75 \text{ Odt}^{-1}$ ($2.19 \text{ GJ}^{-1}$) and $128.47 \text{ Odt}^{-1}$ ($6.59 \text{ GJ}^{-1}$). The calculated costs in this thesis are in line with the results of similar previous studies.

Although the direct supply chain is the least expensive option for delivering biomass feedstock to the heating plant, it is not a possible option all the times because of the seasonal fluctuations of supply and demand. Meanwhile, transferring all the biomass to the plant via the terminal storage may not be economical. However, there are periods in which the available biomass is sufficient to meet the demand and the biomass collection areas are accessible and direct flow of biomass to the plant is achievable. This fact necessitates developing an optimization model to find an optimal flow of biomass between nodes in the supply network.

In Chapter 4, a linear programming model was developed to determine the optimal flow of biomass from source points and terminal storage to the district heating system. The objective of the optimization model was to minimize the total annual delivery cost of biomass to the district heating system, while considering the constraints related to supply, demand, chipping and storage capacity. The optimal solution indicated that it would cost $176,404 annually to supply this district heating system with woodchips; material cost accounted for 0.66\%, loading cost for 27.72\%, chipping cost for 21.06\%, storage cost for 5.45\%, and transportation accounted for 45.11\%. The total annual delivery cost of forest biomass to the gate of the heating plant in the optimal situation equals $2.62 \text{ GJ}^{-1}$. Comparing this cost with that of natural gas ($6.39 \text{ GJ}^{-1}$) implies that using local forest biomass for generating heat in this district heating system might be economical depending upon the capital and operating costs for the district heating system.
The government of Canada has introduced programs that provide funding to cover a part or the entire investment cost in energy projects. Each program has its own mandates and area of focus.

Some of these federal funding programs are: Sustainable Development Technology Canada (SDTC)\(^{23}\), which supports clean-technology projects by covering up to one-third of the investment costs, Technology Early Action Measures (TEAM)\(^{24}\), which funds a part of investment in modern technologies, and EcoAction Community Funding Program\(^{25}\), which provides grants up to $100,000 for GHG emission reduction projects (BIOCAP 2008).

The Government of British Columbia has also various funding programs for energy projects. For instance, BC Local Government Infrastructure Planning Grant Program\(^{26}\) funds up to $10,000 of community energy feasibility studies. Up to 100% of community energy project costs might be funded by the Innovations Fund and Strategic Priorities Fund\(^{27}\) (BIOCAP 2008).

The majority of federal and provincial funding programs in Canada support community energy projects which can be either bio-energy projects or conventional fossil fuel energy projects. These funding programs may not be sufficient to promote the use of biomass for energy generation. Since biomass availability is a challenge in energy generation from biomass, decision makers might prefer to invest in fossil fuel energy generation, particularly natural gas, and still benefit from the funding programs. To promote biomass utilization for energy generation, not only funding programs, but also environmental incentives are required. In summer 2012, the BC Government redefined natural gas as a clean source of energy (Burgmann 2012), while burning natural gas still generates GHG. Now, the question is “how likely are we going to reduce our

\(^{23}\) www.sdtc.ca

\(^{24}\) www.team.gc.ca

\(^{25}\) http://www.cserv.gov.bc.ca/lgd/infra/infrastructure_grants.htm

\(^{26}\) http://www.cscd.gov.bc.ca/lgd/infra/infrastructure_grants/infrastructure_planning_grant.htm

\(^{27}\) http://www.ubcm.ca/EN/main/funding/gas-tax-fund/program.html
GHG contribution when there is a lack of passion for the climate change issue among policy makers?"

5.2 Limitations and future work directions

5.2.1 Limitations

In Chapter 3, the fuel demand of the district heating system was estimated using monthly average temperatures. Thus, the heat demand calculated in this research reflects a general heat demand and does not take the peak loads into account. Furthermore, the heat demand is proportional to the outside temperature and outside temperature is probabilistic. Thus, using the monthly average temperature to estimate the heat demand might not reflect the heat demand precisely.

For quantifying the available supply, the average harvested volumes in logging sites and the average volume of logs scaled at sawmills over the five year period of 2007 to 2011 was used. There is no certainty that harvesting and sawmill volumes will follow the same pattern in the future.

The storage capacity was estimated using a safety stock level equal to the average demand of the plant in March. This estimation does not include the lead times for transporting biomass from source points to the terminal and from terminal to the plant, and the service level of the terminal storage.

The moisture content and the energy content of biomass were kept constant after chipping and also storage. Storing biomass in a closed space may improve the quality of biomass and this would affect handling and transportation costs of biomass.

For the purpose of optimization model, two chippers were considered for handling the chipping capacity. One was assigned for processing biomass at the source points and one was assigned for processing biomass in the terminal storage. In real conditions, this assignment may not be optimal.
5.2.2 Future work

The author suggests the following directions for the future work:

(1) This work only considers the cost of delivering biomass to the gate of the heating plant. The feasibility study can be extended taking into account the costs of converting biomass to energy. These costs include investment costs for building the plant, conversion technology, operating and maintenance costs, labour cost, and the heat distribution cost. Also, the revenue from sale of produced energy can be taken into account to estimate the profitability of district heat generation.

(2) Not all of the potential biomass resources were considered in this case study. Residues from commercial thinning, residues received at landfills, wastes from small scale harvesting in private woodlots, construction and demolition wastes are other potential sources. There is a potential to connect more buildings to the district heating system.

(3) The amount of emissions saved because of replacing natural gas with woody biomass is not considered in this research. Taking this amount into account may improve the feasibility of forest biomass utilization for district heat generation. The total amount of saved emissions is equal to the amount of emissions avoided due eliminating the open-burning and not using natural gas minus the emissions produced during handling, processing, and transportation of biomass.

According to the limitations of the work the author suggests that:

(1) Variations in moisture content after processing and storage should be incorporated in the feasibility study and the optimization model.

(2) The chipping capacity should be incorporated in an optimization model as a decision variable.
References


Dempster P., Gallo N., Hartsough B., Jenkins B., Tittmann P. (2008). Sponsorship-equipment review agreement number 8CA05704- final report to State of California Department of


Ostergaard P. (2012). The regulation of district energy systems. Pacific Institute for Climate Solutions. Victoria, BC.


